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EVALUATION OF POTENTIAL ENVIRONMENTAL CONTROL SYSTEMS FOR A MACH 3 TROOP TRANSPORT AIRCRAFT

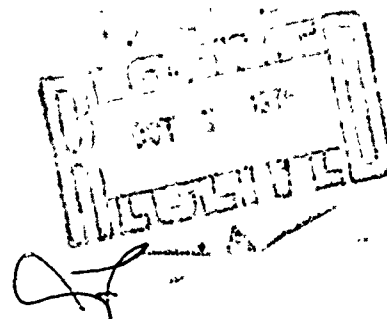
*ENVIRONMENTAL CONTROL BRANCH
VEHICLE EQUIPMENT DIVISION*

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AIR FORCE FLIGHT DYNAMICS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
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a liquid cooled compartment wall, (5) semiclosed vapor cycle environmental control system with a liquid cooled compartment wall and without a water boiler. The last four of the five systems recirculated approximately 50% of the compartment air (250 lb/min) and the rest of the compartment air was exhausted through an ECS heat exchanger. Two types of compartment walls were examined: an air cooled wall and a liquid cooled wall. Fuel was used as the primary heat sink in all the systems. The maximum internal heat load under which each system was analyzed was the same, 158,000 Btu/hr. The total combined maximum internal and external heat load for the first four systems was 417,000 Btu/hr and the fifth system, 577,000 Btu/hr.

Except for the liquid cooled wall, the systems selected for consideration represent a number of different types of basic systems that have appeared previously for supersonic aircraft.

The main criteria used for selecting an environmental control system was based on the weight penalty considerations. The performance of each system was first determined. Then using the Stepwise Integration Method, the total weight penalty was determined for fixed weight, drag, and power conditions in a system. The total weight penalty consisted of fixed weight and jet engine fuel weight that is charged to ECS.

Based on the above selection criteria, the semiclosed bootstrap air cycle environmental control system and semiclosed vapor cycle environmental control system with an air cooled compartment wall were the best choice for the promising systems. The semiclosed bootstrap air cycle environmental control system had the lowest fixed weight, 2523.1 lb. Both systems had the lowest fuel weights, 7211.7 lb for the air cycle ECS and 6,705 lb for the vapor cycle ECS. The semiclosed vapor cycle environmental control system with a liquid cooled compartment wall and without a water boiler could appear to be the best choice if the weight penalty associated with precooling the engine fuel were not considered.

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FOREWORD

This effort was performed in the Environmental Control Branch (FEE), Vehicle Equipment Division, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, during the period from July 1972 to July 1973. The work was done under Project Number 6146, "Aerospace Vehicle Environmental Control," Task 614615, "Control of Thermal Environments in Military Aircraft", with R. J. Watts, Project Engineer. This effort was presented as a thesis project in a cooperative program between the Air Force and the University of Dayton. The author wishes to acknowledge the assistance of Dr. H. N. Chuang of the University of Dayton.

This technical report was submitted March 1975.

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LIST OF SYMBOLS

A	Total heat transfer area, ft^2
A	Constant of integration
a	Ratio of engine specific fuel consumption divided by lift over drag
A_c	Compartment wall area, ft^2
A_f	Heat exchanger free flow area, ft^2
A_{face}	Heat exchanger frontal area, ft^2
b	Constant fuel flow rate for the first segment of flight, lb/min
C'	Heat exchanger coefficient, $(\alpha/2g)^{1/2}$
C''	Heat exchanger coefficient
C_i	Heat exchanger weight constant
c_p, c_v	Specific heat at constant pressure and constant volume, Btu/lb-°F
D	Diameter, ft
D_s	Specific diameter
D_{t_k}	Drag, lb
f	Fanning factor
g	Gravitational acceleration, ft/sec^2
H	Fluidic head, $\text{ft-lb}_f/\text{lb}_m$
h	Heat transfer coefficient, $\text{Btu}/\text{sec-ft}^2\text{-}^\circ\text{F}$
h_a	Altitude, ft
h_l	Latent heat of water, Btu/lb
hp	Horsepower

LIST OF SYMBOLS (CONTINUED)

j	Colburn's modulus
K	Constant for heat exchanger design
k	Conductivity, Btu/hr-°F-ft
L	Lift, lb
L'	Length of cooling wall tubes per ft ² of compartment wall, ft/ft ²
L _c	Length of compartment, ft
M	Weight, lb
M	Mach number
M _c	Water boiler container weight, lb
M _{dw}	Total fixed weight charged to ECS unit except for expendable coolant and fuel used and insulation, (M _{ecse} - 0.25M _e), lb
M _e	Total weight of expendable used
M _{ecs}	Weight of ECS components, lb
M _{ecse}	Fixed weight charged to ECS component and engine weight penalty, M _{ecs} + M _{eh} + M _{th} , lb
M _{eh}	Engine weight penalty for horsepower generation, lb
M _{hc}	Heat exchanger core weight, lb
M _m	Freon compressor motor weight, lb
M _{mf}	Fan motor weight, lb
M _{te}	Total weight of expendable coolant plus 25% reserve supply, lb
M _{tf}	Fan and motor weight, lb

LIST OF SYMBOLS (CONTINUED)

M_{th}	Engine weight penalty for engine thrust, lb
M_{tw}	Total fixed weight of the ECS excluding fuel weight, ($M_{ecse} + 1.25M_e + M_{in}$), lb
M_{wa}	Weight of air cooled wall, lb
M_{wl}	Weight of liquid cooled wall, lb
N	RPM
n_r	Recovery factor
N_s	Specific speed
NTU	Number of heat transfer units
P	Pressure, psia
P_c	Perimeter of a cross-section of the compartment wall, ft
Pl_f	Fuel penalty except for fuel expended due to thermal insulation, lb
Pl_t	Total fixed and fuel weight penalty, ($Pl_{TOT} - W_{in}$), lb
Pl_{TOT}	Total fixed and fuel weight penalty except for insulation, ($W_{dw} + W_{Tb} + W_{Tr} + W_{hp} + W_{Te}$), lb
Pl_{Ts}	Total fuel penalty, lb
Pr	Prandtl's number
sfc	Thrust specific fuel consumption, lb fuel per lb thrust per hour
sfc'	Horsepower specific fuel consumption, lb/fue"/hp-hour
SEWHP	Specific engine weight per hp, lb/hp
SEWT	Specific engine weight per lb of thrust, lb/lb _f
T	Temperature, °R

LIST OF SYMBOLS (CONTINUED)

t	Time, hr
T_{ai}, T_{ao}	Air temperature into and out of the compartment, °R
T_{ct}	Average temperature in the compartment, °R
Th	Drag, lb_f
U	Overall heat transfer coefficient, $Btu/sec-ft^2-°F$
u	Velocity, ft/sec
u_{rho}	Exhaust air velocity through the heat exchanger nozzle, ft/sec
V	Volume, ft^3
\dot{V}	Volume flow, ft^3/sec
V_b	Volume of boiler, ft^3
w	Fixed weight
\dot{W}	Mass flow rate, lb/min
W_{dw}	Fixed weight penalty of M_{dw} , lb
W_{e1}, \dot{W}_{e3}	Flow rate of expendable coolant at Mach 1 and Mach 3 condition, lb/min
\dot{W}_{fb_i}	Constant fuel flow rate expended for the "i" segment of flight required to obtain engine bleed pressure, lb/min
\dot{W}_{fdb_i}	Constant fuel flow rate expended for the "i" segment of flight due to drag of bleed air, lb/min
\dot{W}_{fh_i}	Constant fuel flow rate expended for the "i" segment of flight due to horsepower penalty, lb/min
W_{fe}	Fuel used in carrying expendable coolant, lb
W_{fr}, W_{fr_o}	Extra fuel expended in carrying the fuel W'_{fr} (for the total flight, subscript "o"), lb
W'_{fr}	Fuel that is expended in the engine so that additional amount of thrust produced will offset the drag loss, lb

LIST OF SYMBOLS (CONTINUED)

\dot{W}_{fr_i}	Constant fuel flow rate expended for the "i" segment of flight, due to ram air penalty (drag), lb/min
\dot{W}_{frb_i}	Constant fuel flow rate expended for the "i" segment of flight, due to bleed air penalty, lb/min
W_{fs}, W_{fs_0}	Fuel weight penalty expended due to fixed weight of the environmental control system (for the total flight, subscript "o"), lb
W_{hp}, W_{hp_0}	Weight of the fuel expended due to shaft horsepower extraction penalty (for the total flight, subscript "o"), lb
W'_{hp_i}	Factor, $(sfc'_i \cdot hp_i) (W'_i/60)$
W'_i	Factor, $\left((\exp(x_i) - 1)/a_i \right) \exp \sum_{j=1}^{x-1} x_j$
W_{in}	Weight of thermal insulation and fuel expended, lb
W_s	Cooling system fixed weight, lb
W_{Tb}, W_{Tb_0}	Weight of the fuel expended due to bleed air penalty (for the total flight, subscript "o"), lb
W'_{Tb_i}	Factor, $(\dot{W}_{fb_i} - \dot{W}_{fdb_i}) W'_i$
\dot{W}_{tc}	Total compartment air flow, lb/min
W_{Te}, W_{Te_0}	Weight of the expendable used for the flight plus weight of the fuel expended for the total flight due to the expendable penalty (for the total flight, subscript "o"), lb
W_{Tr}, W_{Tr_0}	Weight of the fuel expended due to ram air penalty (for the total flight, subscript "o"), lb
$\dot{W}_{Tr_1}, \dot{W}_{Tr_3}$	Total ram air flow at Mach 1 and Mach 3 flight condition, lb/min
W_{Ts}, W_{Ts_0}	Fixed weight plus weight of the fuel expended (for the total flight, subscript "o"), lb
\dot{W}_{wl}	Liquid flow in liquid cooling wall, lb/min

LIST OF SYMBOLS (CONTINUED)

X	Length, ft
x_i	$(at)_i$, Dimensionless time parameter
Y	Weight penalty of the fuel expended, lb
Z	Heat exchanger flow stream capacity rate ratio for sides 1 and 2, $\dot{W}_1 c_{p1} / \dot{W}_2 c_{p2}$
Z_m	Power balance factor due to frictional and other mechanical losses for cooling turbine/bootstrap compressor
GREEK:	
α	$Pr \ 0.667 / c_p$
γ	Ratio of specific heats, c_p / c_v
Δ	Difference
ΔT_{af}	Temperature difference between the air entering the air gap in the compartment wall and air leaving the air gap in the wall, °R
ΔT_{ec}	Isentropic temperature difference between ram air and bleed air from the engine compressor, °R
ΔT_f	Increase in the temperature due to exhaust air being circulated through a fan, °R
ΔT_{fc}	Isentropic total temperature change between the freon compressor inlet and outlet, °R
ΔT_{in}	Temperature difference between the fuselage skin and cooling plate, °R
ΔT_{lf}	Temperature difference between the liquid going into the compartment wall passages and liquid exhausting out of the wall, °R
η	Air-side heat exchanger temperature effectiveness or efficiency
η_o	Total surface temperature effectiveness

LIST OF SYMBOLS (CONTINUED)

η_r	Ram air recovery factor
ρ	Density, lb/ft ³
l	Heat exchanger length, ft.

SUBSCRIPTS:

a	Ambient condition
al	Aluminum wall
aw	Air wall
b	Engine bleed air
c	Bootstrap compressor
ci, co	Bootstrap compressor inlet and outlet
Ci, Co	Freon compressor inlet and outlet
cw	Compartment wall
e	Expendable coolant
ec	Point at engine compressor where bleed air is tapped off
f	Fan
fc	Freon Compressor
hx	Heat exchanger
i,j,k,n	Interval index
in	Insulation
l	Liquid
r	Ram air
s	Shaft
t	Cooling turbine
tc	Cooling turbine/bootstrap compressor

LIST OF SYMBOLS (CONTINUED)

ti, to	Cooling turbine inlet and outlet
w	Water
1,2,3	Numerals are for location or segment purpose

SECTION I

INTRODUCTION

The purpose of this effort is to examine various environmental control systems (ECS) that appear promising for Mach 3 supersonic troop transport application.

Aircraft need compartment pressurization and air conditioning because the extreme speeds and altitudes at which they operate adversely affect the passengers and equipment. The compartment pressurization system is used to maintain and regulate a safe and comfortable pressure level for passengers inside the compartment. An air conditioning system is needed to maintain a comfortable temperature level and fresh air requirement inside the compartment.

Present transport aircraft, which are classified as subsonic, use either a bootstrap air cycle system or vapor cycle system to meet their air conditioning needs. In a bootstrap air cycle system, as shown in Figure 1, high pressure air extracted from the engine compressor is expanded through a turbine causing a decrease in temperature and is then used to cool the compartment air. The turbine is loaded with a bootstrap compressor because added cooling capacity can be obtained by boosting the pressure through the compressor. The air from the engine and bootstrap compressors is cooled by ram air through heat exchangers. In the vapor cycle system, as shown in Figure 2, the engine compressor bleed air is cooled through a primary heat exchanger using ram air as heat sink and an evaporator so that it can be used to cool the compartment air.

With the advent of the supersonic transport, new subsystems have been added in the aircraft environmental control system for the Concorde. The Mach 2 Concorde environmental control system will be defined here to illustrate the type of first generation cooling system (References 1 and 2). Because of the excessive aerodynamic heating associated with Mach 2 flight, the fuselage is provided with thermal insulation to reduce

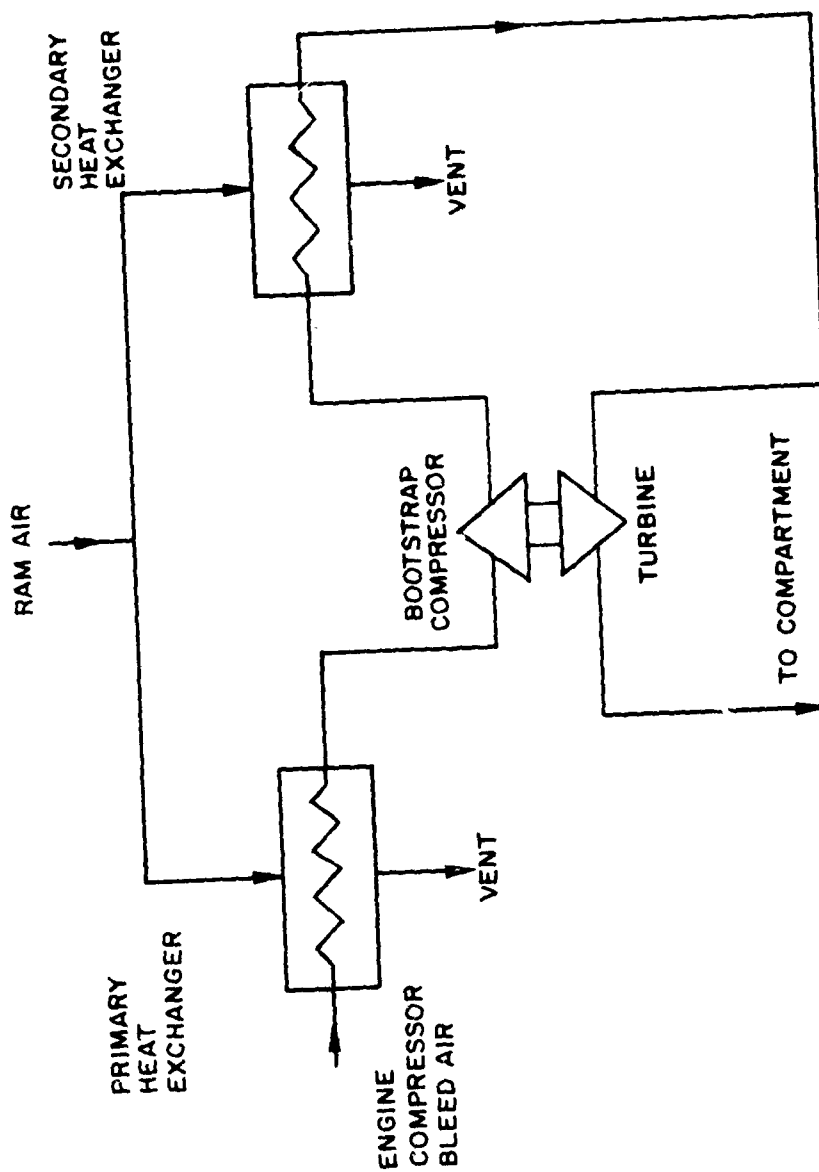


Figure 1. Bootstrap Air Cycle Air Conditioning System

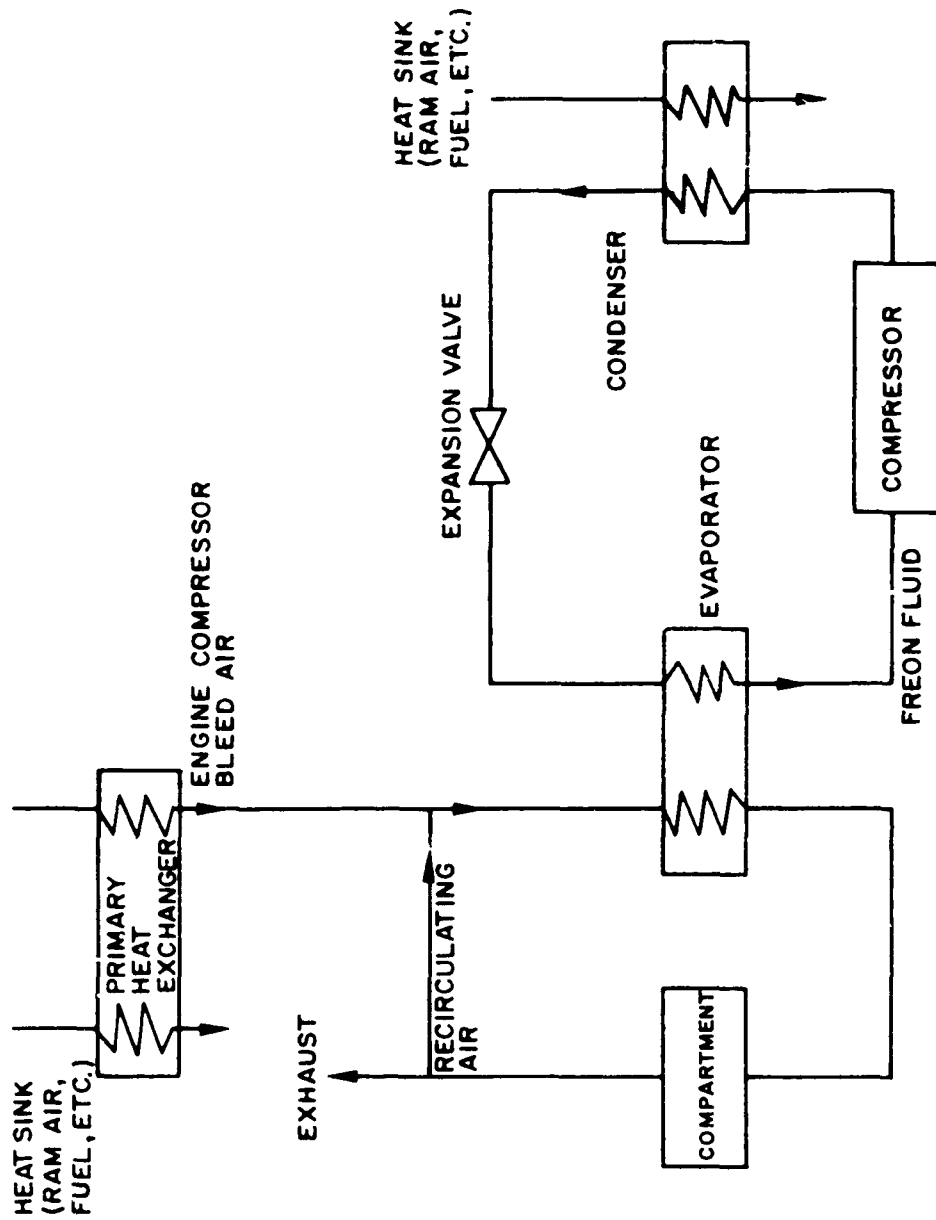


Figure 2. Vapor Cycle Air Conditioning System

the heat transmission. Air flows in compartment wall channels to collect the heat transmitted through the insulation. Fuel at rather low temperature is also used to supplement ram air as a heat sink since ram air taken on board is at a moderately higher temperature. The Concorde system is similar to the bootstrap cycle as shown in Figure 1 but includes, in addition, a fuel/bleed air heat exchanger between the secondary heat exchanger and turbine, and a compartment cooling wall containing exhaust air. A schematic diagram showing the construction of the air-cooled compartment wall is shown in Figure 3.

Three identical environmental control systems (ECS1, ECS2, ECS3) are used to distribute the cool air to the passenger compartment, crew compartment and electronic equipment bay as shown in Figure 4. This design is preferred over a system with only one ESC since the probability of total failure is much greater for the system with one ECS. These designs are mostly of semiclosed systems type, except for the open bootstrap cycle which exhausts all compartment air through Heat Exchanger Number 2 and then overboard as shown in Figure 5. The ram and bleed air temperature are moderately high for Mach 3 conditions. By recirculating part of the compartment air, less bleed air is required for the environmental control system. Since less bleed air is required, less fuel is required for cooling the bleed air. For all three ECS the rate of conditioned air delivered to the compartment is the same, 166.7 lb/min. Since all cycles use exhaust air out of the compartment for cooling the wall, they will be defined as regenerative cycles. For this study, the semiclosed cycles will recirculate approximately 50% of the compartment exhaust air through an odor and contaminate remover, then mix with the cool air from the air turbine or evaporator and return to the compartment. For the air cycle, the remaining compartment exhaust air is vented through Heat Exchanger Number 2 and then exhausted overboard as shown in Figure 6. For the vapor cycles shown in Figures 7 and 8, the remaining air is used as a heat sink for the condenser before it is finally exhausted. And for the vapor cycle shown in Figure 9, the remaining air is used as a heat sink for the air/air heat exchanger and precooled fuel was used to cool the bleed air.

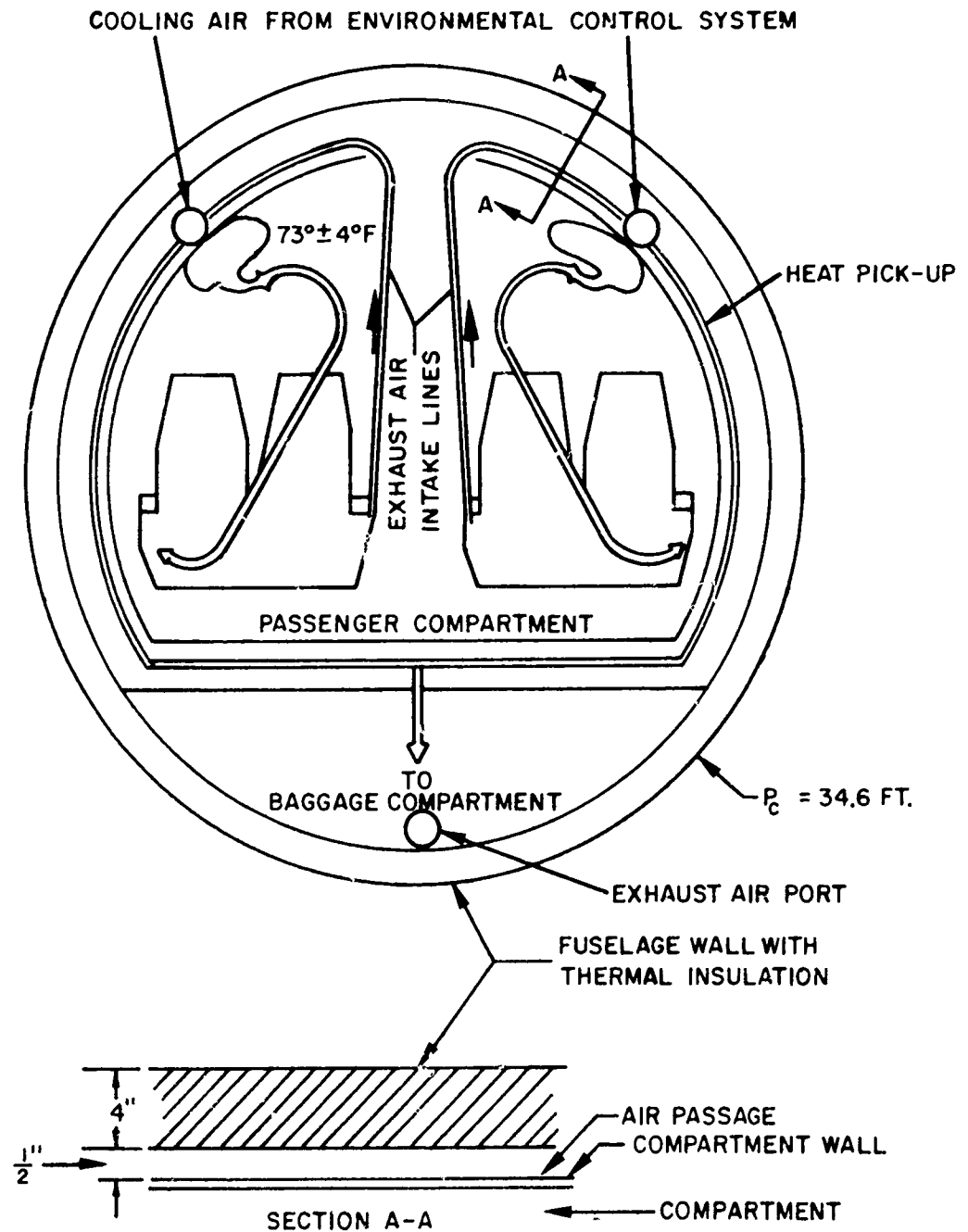


Figure 3. Air Cooled Compartment Wall

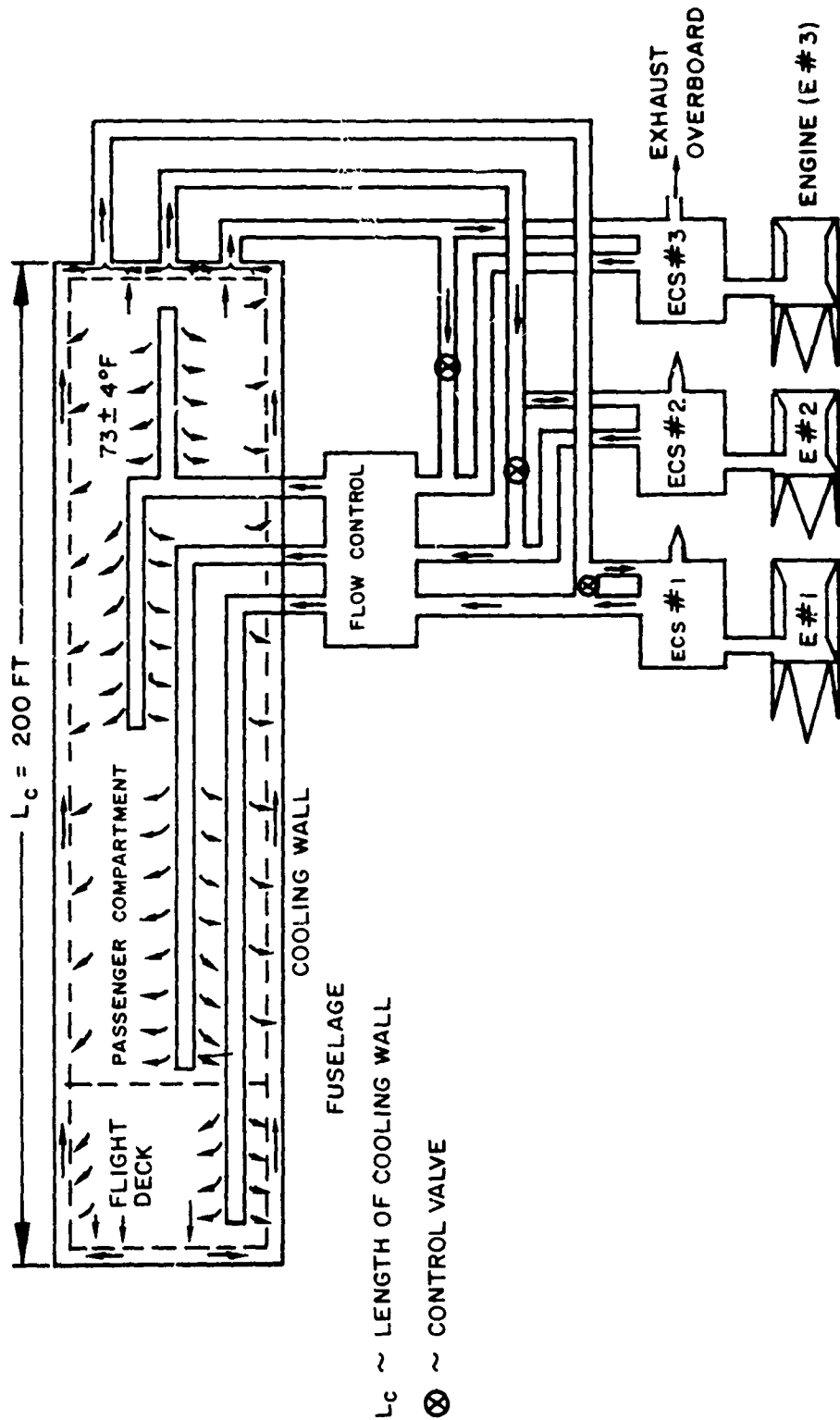


Figure 4. Environmental Control System for Mach 3 Supersonic Transport

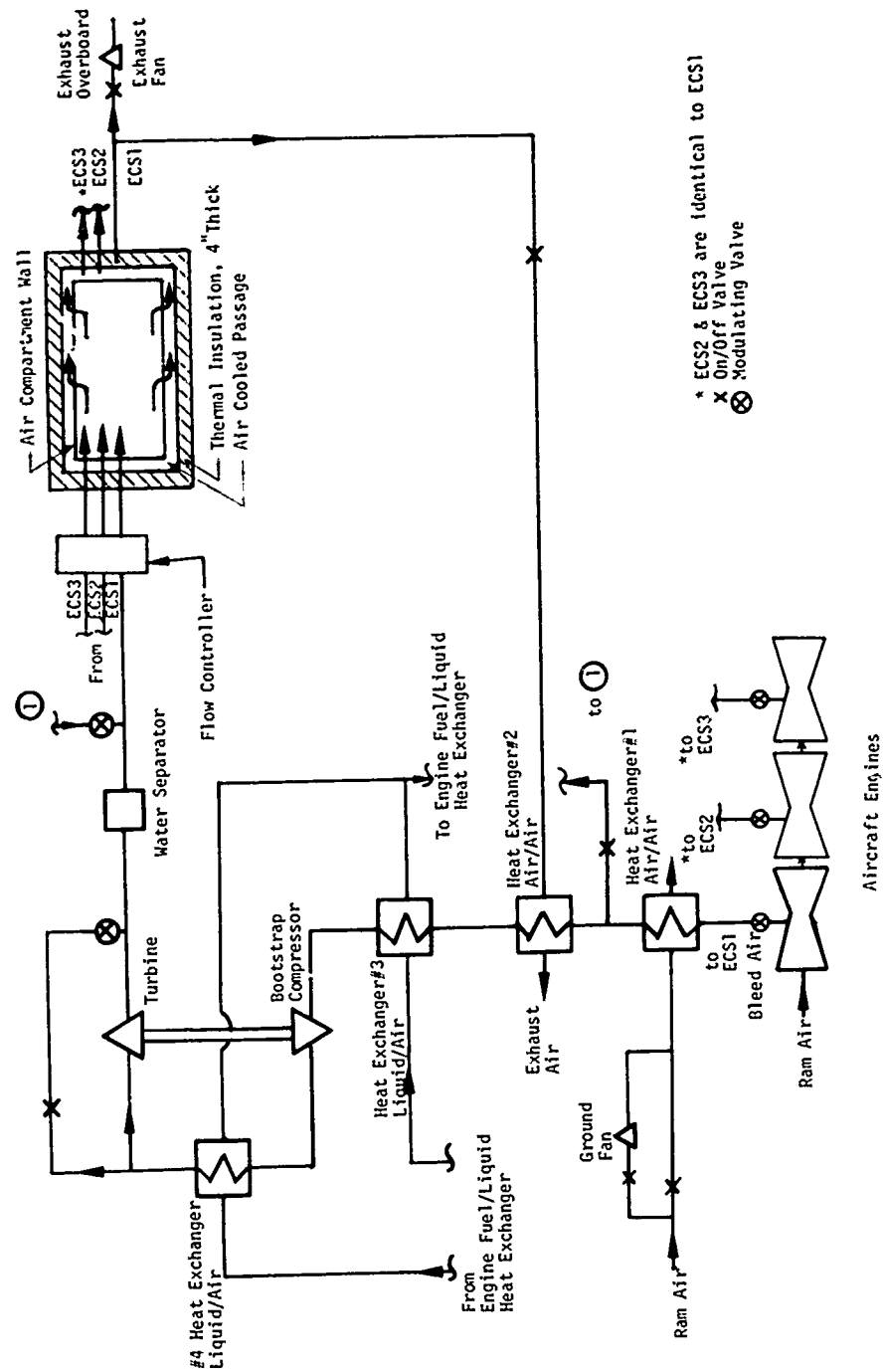


Figure 5. Schematic, Bootstrap Air Cycle Environmental Control System with Air Cooled Wall

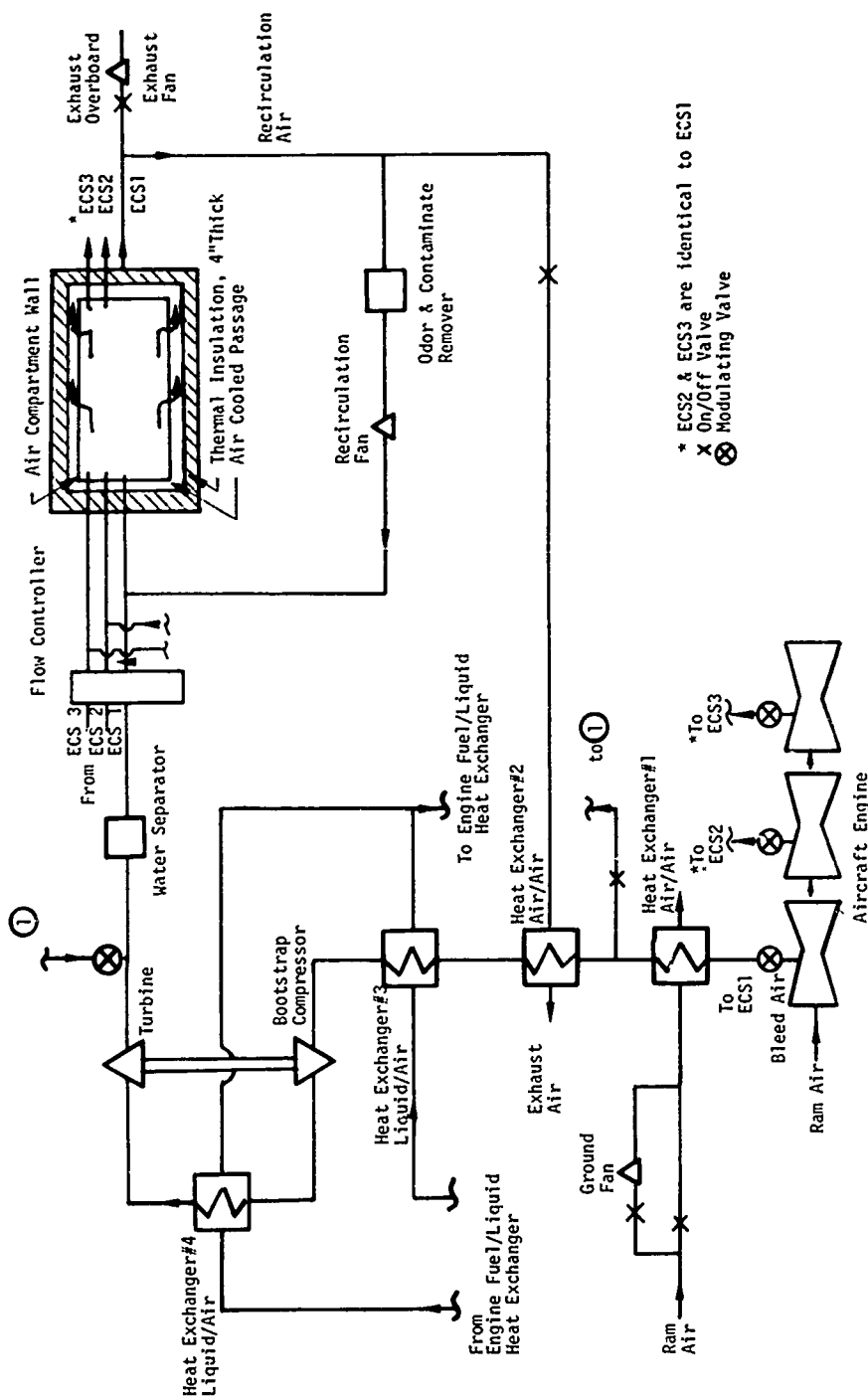


Figure 6. Schematic-Semiclosed Bootstrap Air Cycle Environmental Control System with Air Cooled Wall

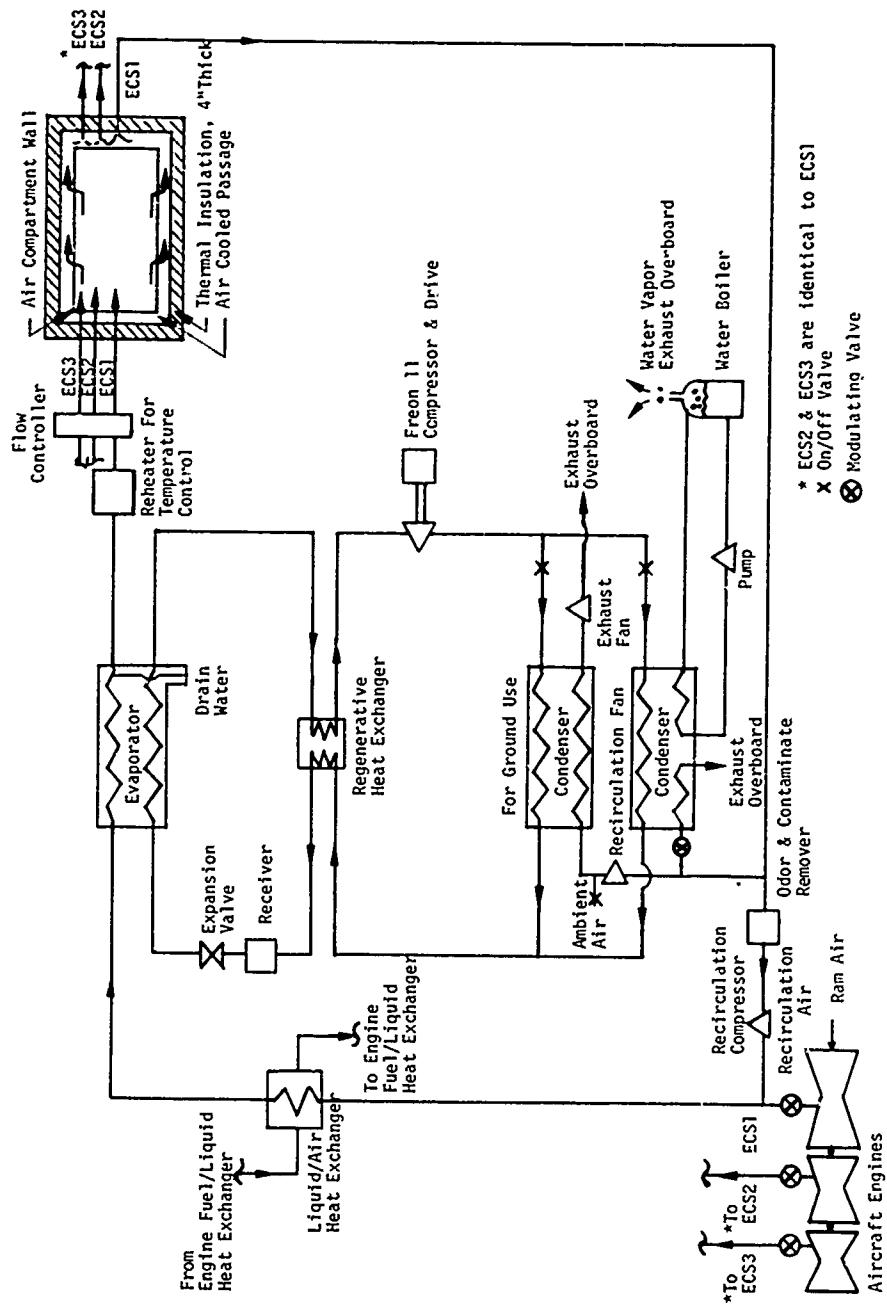


Figure 7. Schematic, Semiclosed Vapor Cycle Environmental Control System with Air Cooled Wall

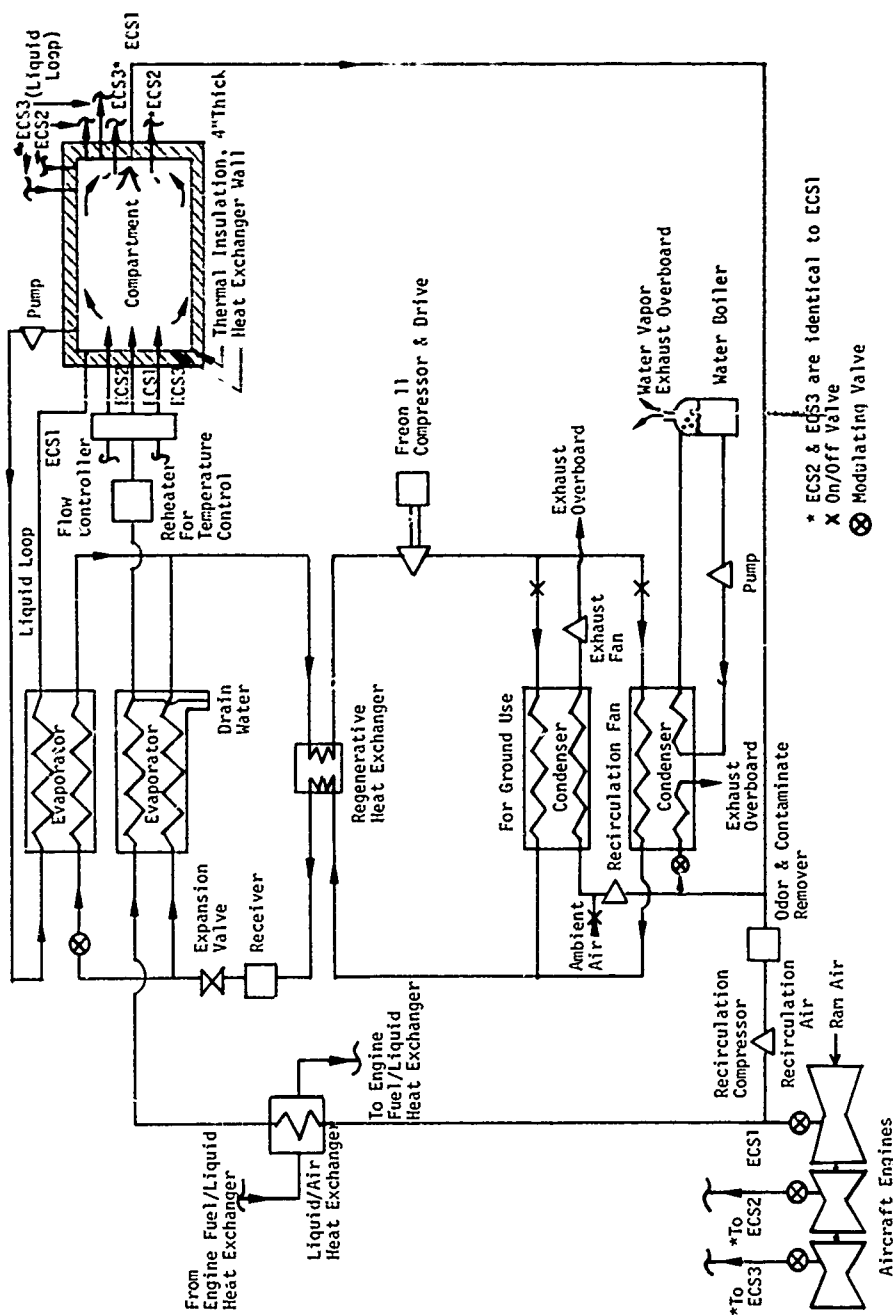


Figure 8. Schematic, Semiclosed Vapor Cycle Environmental Control System with Liquid Cooled Wall

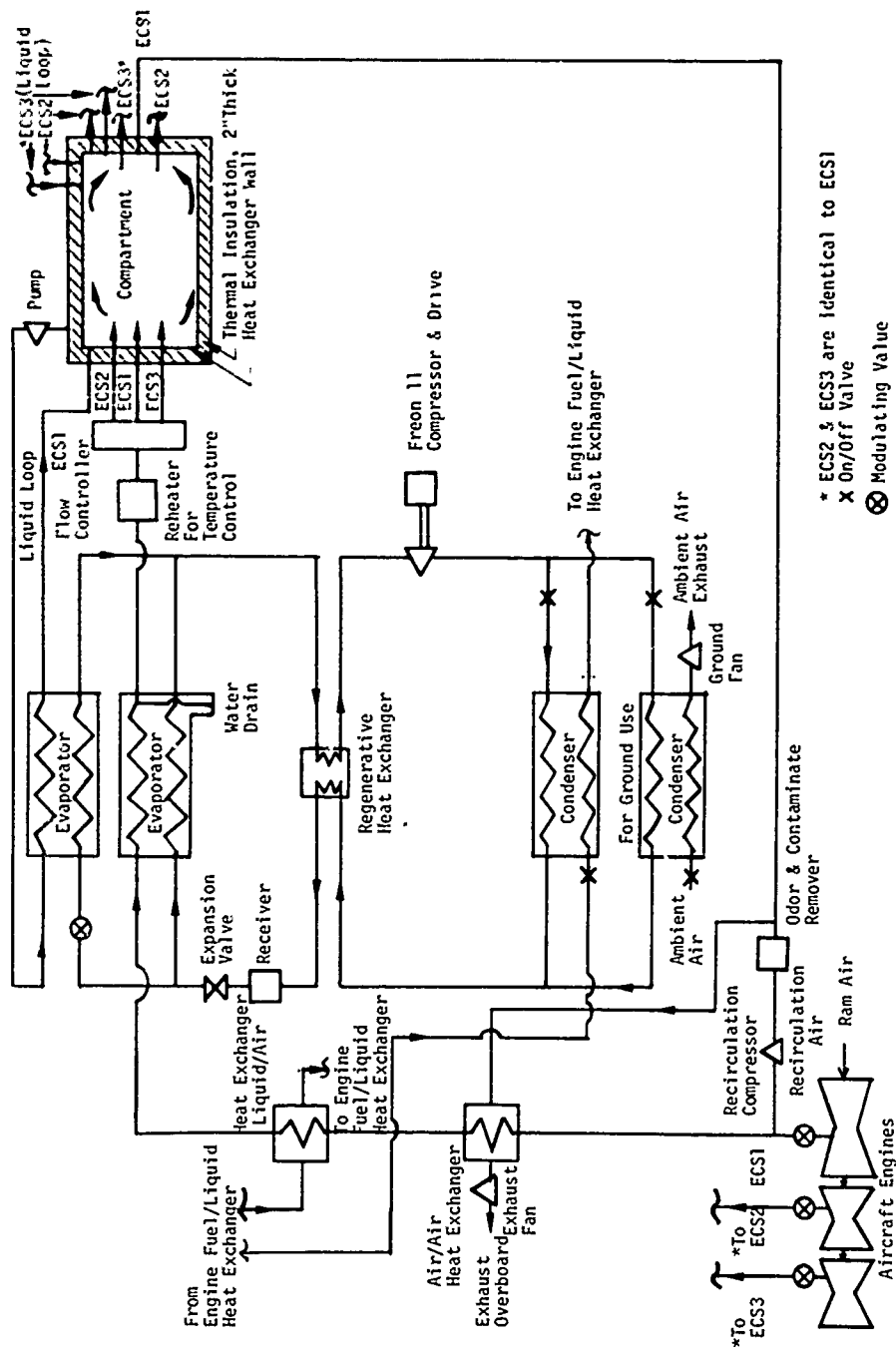


Figure 9. Schematic, Semiclosed Vapor Cycle Environmental Control System with Liquid Cooled Wall/Without Water Boiler

The aircraft selected for the study was a supersonic transport type aircraft capable of carrying 256 passengers and crew at Mach 3 speed. The air cycle and vapor cycle environmental control systems selected for consideration for this type of aircraft were (Figures 5 through 9):

1. Cycle A-1 Bootstrap Air Cycle Environmental-Control System with an air cooled compartment wall (Figure 5).
2. Cycle A-2 Semiclosed Bootstrap Air Cycle Environmental Control System with an air cooled compartment wall (Figure 6).
3. Cycle V-1 Semiclosed Vapor Cycle Environmental Control System with an air cooled compartment wall (Figure 7).
4. Cycle V-2 Semiclosed Vapor Cycle Environmental Control System with a liquid cooled compartment wall (Figure 8).
5. Cycle V-3 Semiclosed Vapor Cycle Environmental Control System with a liquid cooled compartment wall and without a water boiler (Figure 9).

Hereafter, the word "cycle" is synonymous with any specific ECS under discussion.

The coolant to be considered for the fluid cooled compartment walls will be either a silicone type cooling fluid or air (as illustrated in Figures 4 and 10). For the liquid cooled wall configuration, the fluid flows through a tube/fin aluminum heat exchanger wall. For the air cooled wall configuration, air is exhausted through the compartment wall. For both cases, the fluid coolant absorbs most of the aerodynamic heat leak through the fuselage thermal insulation.

In summary, the total weight penalty, sizing of environmental control system components, and performance will be determined for each environmental control system. The merit of each system will be based on its take-off weight in terms of the fixed environmental control system weight, fuel weight charged to the components, and the sum of these two weights, defined as the total weight penalty. The selection of the most promising system will be based on which system would possess the least total weight penalty. The fuel weight mentioned above can be broken down into: (1) fuel expended by the airplane in carrying the fixed weight of ECS components, (2) fuel used to operate the engine compressor in obtaining

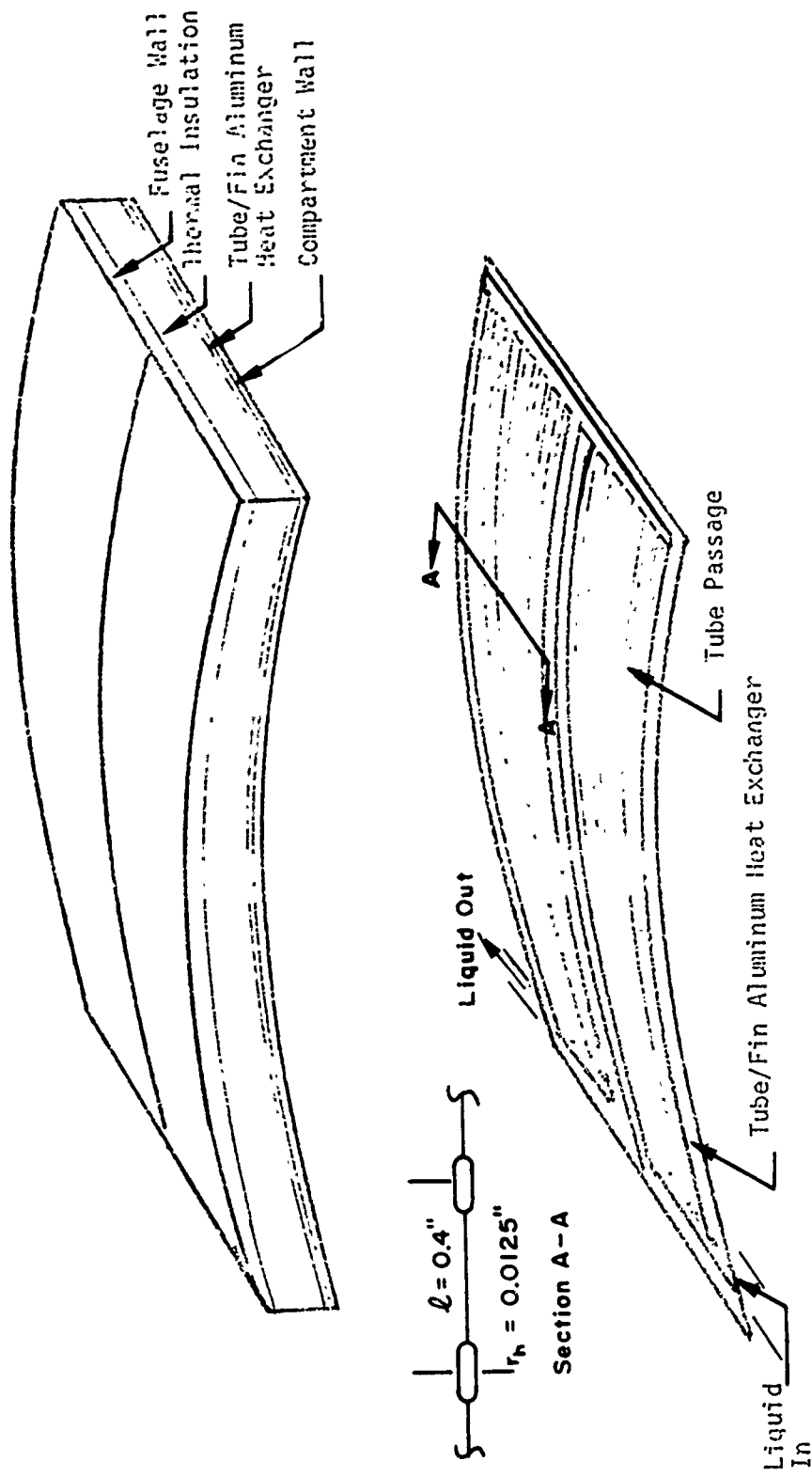


Figure 10. Liquid Cooled Compartment Wall

pressurized bleed air, (3) fuel used in obtaining thrust power to overcome ram air drag which is used as coolant in heat exchangers, (4) fuel used to meet horsepower requirements for running various components of the system.

In the design of the environmental control systems, the individual components will be sized (weight, volume, etc.) for a particular segment of flight, based on a maximum constraint such as heat load or flow rate and will be defined as the design point condition. The operation of the components at other flight conditions will be defined as off-design point conditions. After sizing the components, the performance of each environmental control system will be determined and the weight penalty calculated.

SECTION II

DESCRIPTION OF THE PROPOSED ENVIRONMENTAL CONTROL SYSTEMS

1. INTRODUCTION:

In this section the description and operation of the proposed environmental control systems is presented. The environmental conditions assumed for the Mach 3 type transport aircraft are given in order to show the scope of this study and a description of the environmental control components is listed. The operation of each environmental control system is described for Mach 3 and Mach 1 flight operations and for ground operation.

2. ENVIRONMENT OF OPERATION

The aircraft flight profile selected for this study is shown in Figure 11. The flight profile was divided into five segments. The first segment was ground operation before take-off. The second segment included take-off, climb, and subsonic flight over inhabited land where the aircraft was limited to speeds slightly under Mach 1 to avoid excessive noise and possible shock wave damages. The third segment was Mach 3 flight over uninhabited areas such as ocean and arctic areas. The fourth segment of the flight involved reducing of both speed and altitude prior to landing and the landing itself. The fifth segment was taxi and waiting for ramp space. The speed was assumed constant through each segment as shown in Figure 11.

The environment of the compartment must be maintained within specific comfort and safety limits. Experiences gained in current aircraft operations were used as a guide line in providing the proper compartment air temperature, pressure, composition, ventilation rate, and odor level. The normal ventilation rate selected for the passengers is 20 cfm per person. Under normal operating condition, the compartment pressure was maintained between 11 psia and 15 psia. The rate of change of compartment pressure should not exceed 0.3 psi per minute during depressurization or 0.1 psi per minute during pressurization.

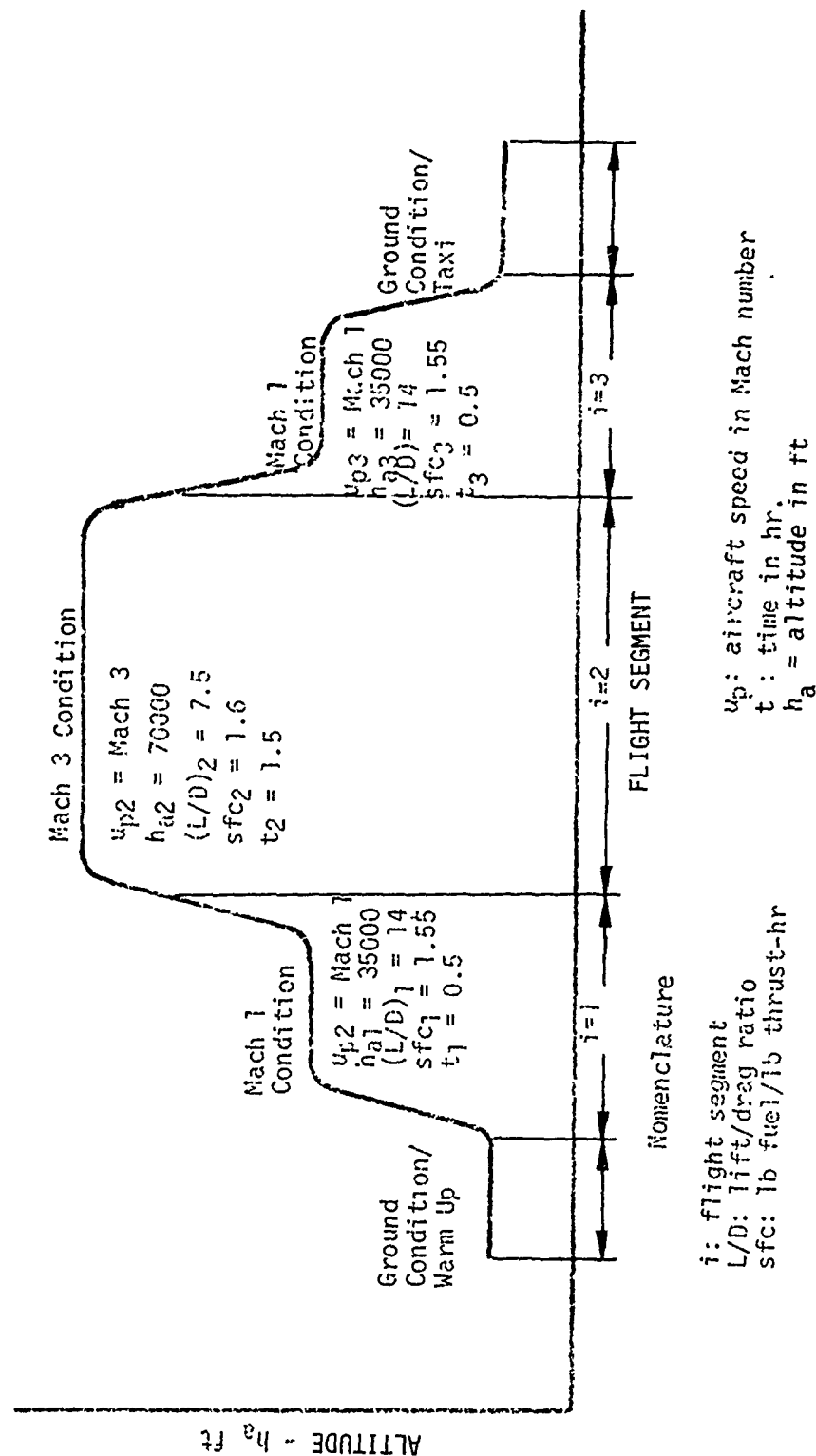


Figure 11. Flight Profile for Mach 3 Commercial Aircraft

A desirable environmental system should be capable of maintaining stable dry bulb compartment temperature, as well as proper air movement, humidity, compartment pressure altitude, and other factors to provide a comfortable quarter for the majority of passengers. This comfortable compartment condition is an effective temperature ranging from 66°F to 77°F. The effective temperature is an index which correlates the combined effects of dry bulb air temperature, air humidity, and air movement upon human comfort.

3. DESCRIPTION OF THE AIR CYCLE ENVIRONMENTAL CONTROL SYSTEM

In this subsection the description of the two air cycle environmental control systems, Cycles A-1 and A-2, as shown in Figures 5 and 6, is given; by describing the components and subsystems in paragraphs 3a and explaining the operation of cycles in Paragraphs 3b and 3c.

a. Description Of Air Cycle Components and Subsystems

The bootstrap and semiclosed bootstrap environmental control system have similar components except for the recirculation air loop used in the semiclosed bootstrap system. In both systems the amount of air circulated through the compartment was the same. The components were sized for slightly different conditions for each system because the bleed air flow was less for the semiclosed system. The following is a brief description of those components used in the environmental control systems for Cycles A-1 and A-2.

(1). Turbine/Bootstrap Compressor Machine

The turbine/bootstrap compressor machine was selected for the air cycle systems under consideration because this type of machine is used in both the Concorde design and the proposed Boeing supersonic transport design (Reference 1). The turbine is loaded with a bootstrap compressor since added cooling capacity can be obtained by boosting the pressure through the compressor. The turbine/bootstrap compressor machine uses a centrifugal geometry design as shown in Figure 12. The flow direction indicated is for a radial turbine and with flow direction reversed, the

results apply to a centrifugal compressor.

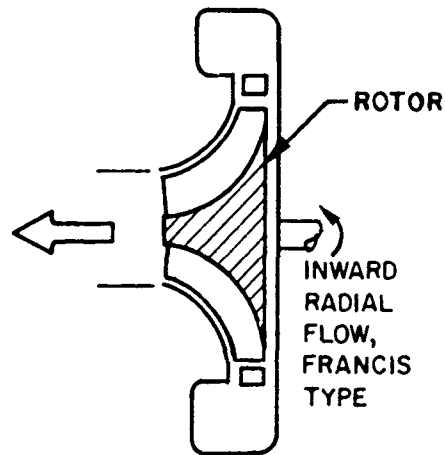


Figure 12. Radial-Flow Turbine

(2). Heat Exchangers

The type of heat exchangers used to cool the bleed air at different points in the system were: Heat Exchanger Number 1 using bleed air and ram air, Heat Exchanger Number 2 using bleed air and exhaust air, and Heat Exchangers Numbers 3 and 4 using bleed air and liquid.

The heat exchangers had compact cross-flow cores with either plate/fin or tube/fin construction as shown in Figures 13 and 14. Even though the counter-flow arrangement is thermodynamically superior to the single-pass cross-flow arrangement its overall size and weight, including manifolds and transition ducts, will always be greater than the single-pass cross-flow arrangement.

Heat Exchanger Number 1 had a tube/fin core with bleed air flowing inside the tube. The core was made of a special high temperature stainless steel due to high engine bleed air temperature and pressure for Mach 3 aircraft speed. Heat Exchanger Number 2 had a plate/fin stainless steel core. Heat Exchangers Numbers 3 and 4 had a tube/fin aluminum core with a coolant fluid flowing inside this tube.

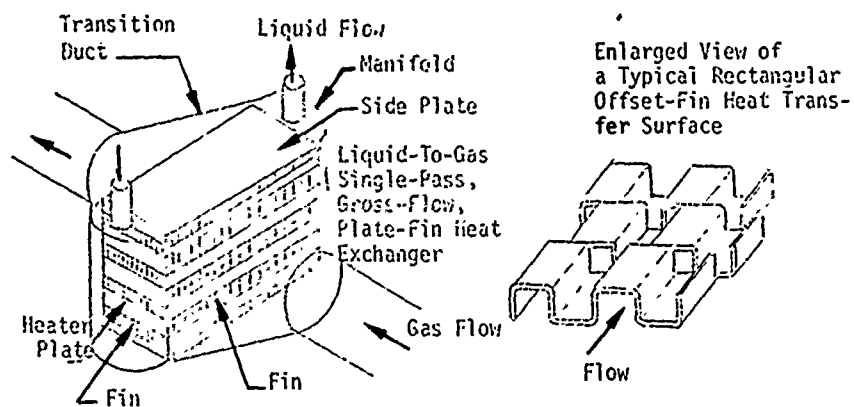


Figure 13. Core Geometry and Heat Transfer Surface for a Typical Plate-Fin Heat Exchanger

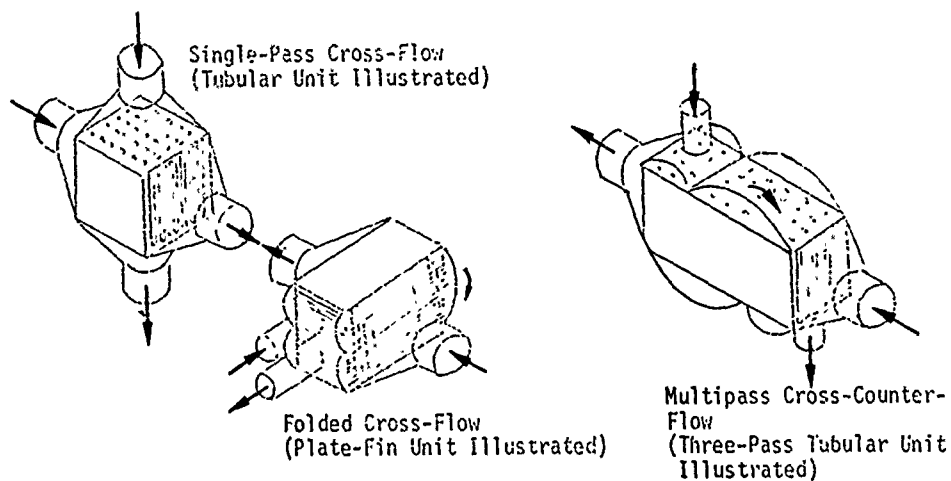


Figure 14. Cross Flow, Tube-Fin Heat Exchanger Arrangements

(3). Fan

The fans selected in Cycles A-1 and A-2, such as the exhaust and ground fan, used an axial flow type blade and were powered by an electric motor.

(4). Odor and Contaminate Remover

Activated charcoal filters were installed in the compartment recirculation system to satisfy the ventilation design requirement of providing a minimum air ventilation rate of 20 cfm air per passenger consisting of 10 cfm of fresh air plus sufficient conditioned recirculation air to result in an equivalent of 20 cfm or more fresh air per passenger. This unit will remove smoke and odor contaminate from the air and rejuvenate the air to essentially fresh air standard.

(5). Water Separator

The water separator, used to remove entrained water in turbine exhaust air for ground operation, had a fibrous cone sock which coalesced the water particles and a water separation section which removed the water as shown in Figure 15.

(6). Transport Liquid Loop Subsystem for Heat Exchangers
Numbers 3 and 4

The transport liquid loop subsystem consisted of a liquid loop, Heat Exchangers Numbers 3 and 4, and the liquid/fuel heat exchanger as shown in Figure 16 and was used to cool the bleed air with a fuel heat sink. The liquid used was silicone type fluid with a wide operating temperature range between -130F to 400F (Reference 3). Direct cooling of the bleed air with a bleed air/fuel heat exchanger was not possible since the fuel would be subject to localized temperatures above the flash point.

(7). Ram Air Subsystem For Heat Exchanger Number 1

The ram air subsystem used for Heat Exchanger Number 1 is shown in Figure 17. For Mach 3 operation, the ambient air entered the ram air

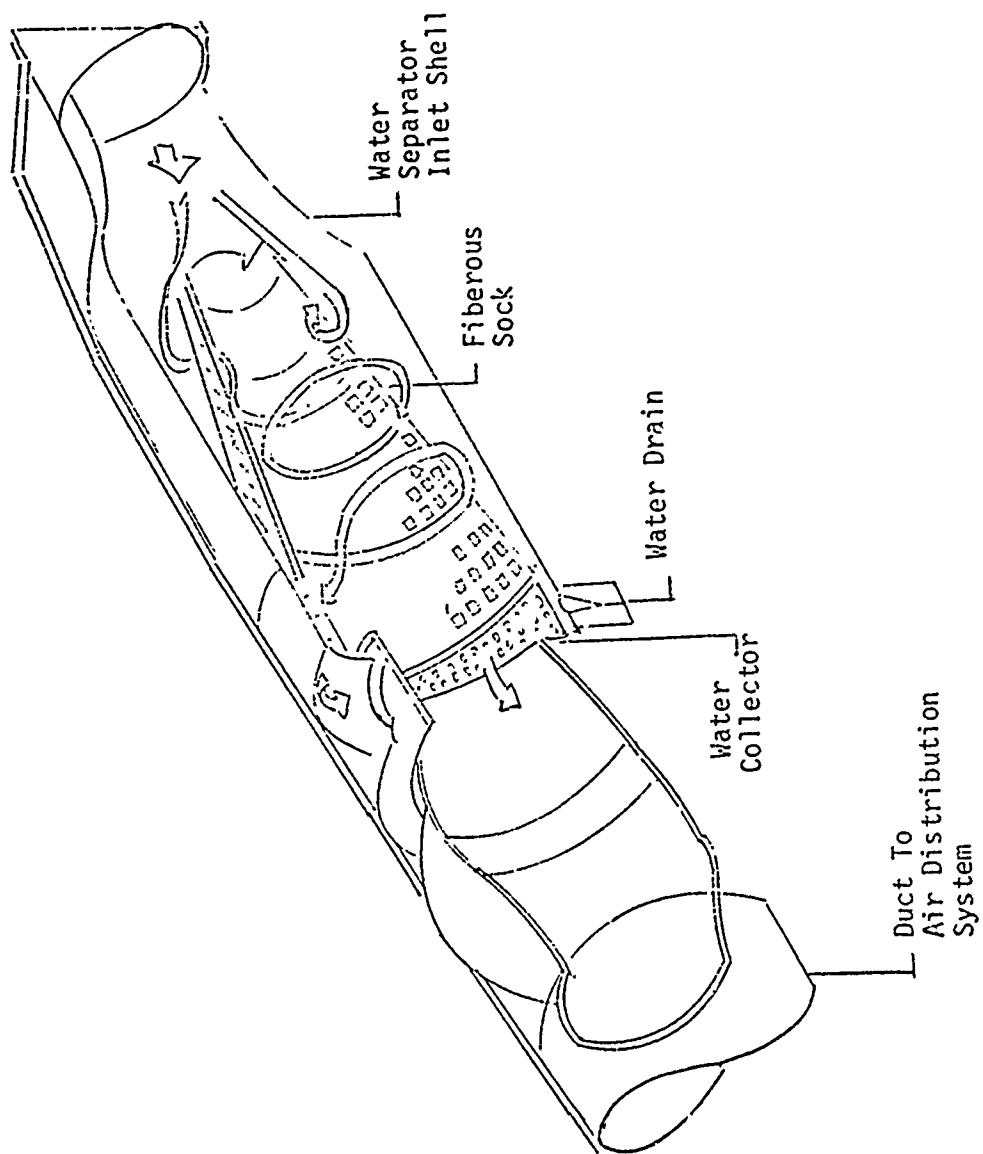


Figure 15. Cut Away View of Water Separator

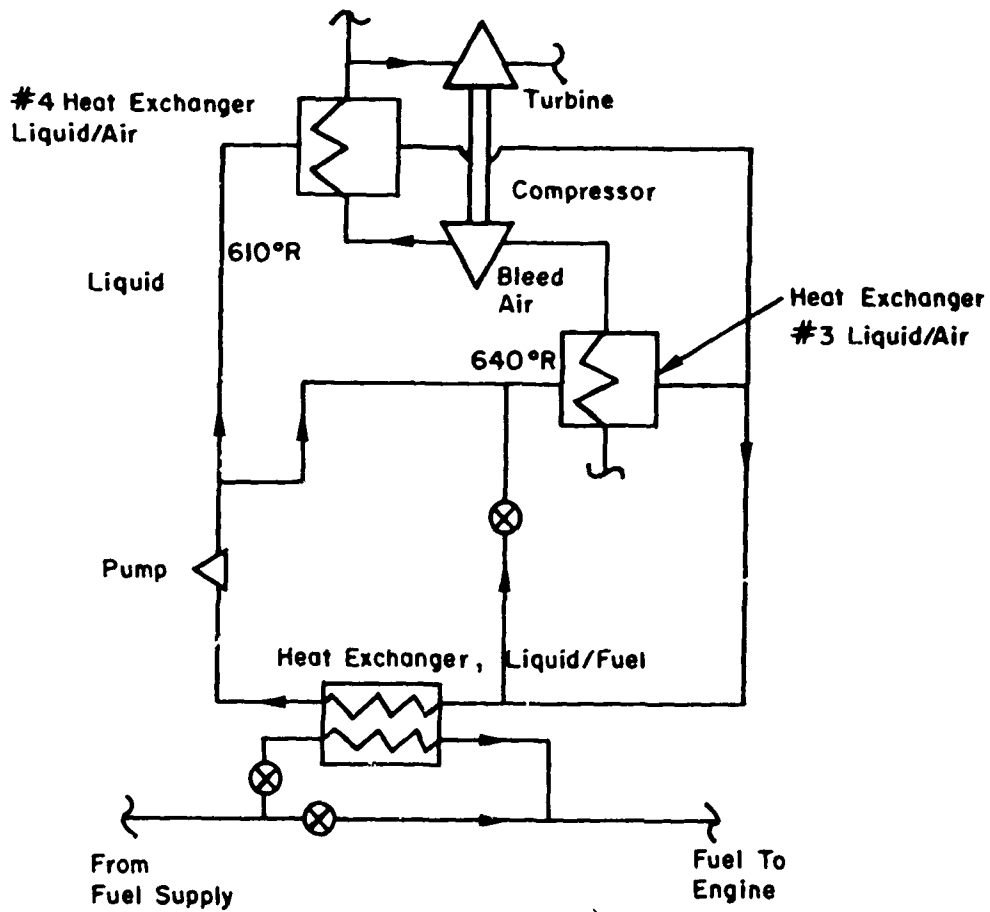


Figure 16. Transport Liquid Loop Subsystem/Used to Transfer Heat from the Bleed Air to the Fuel

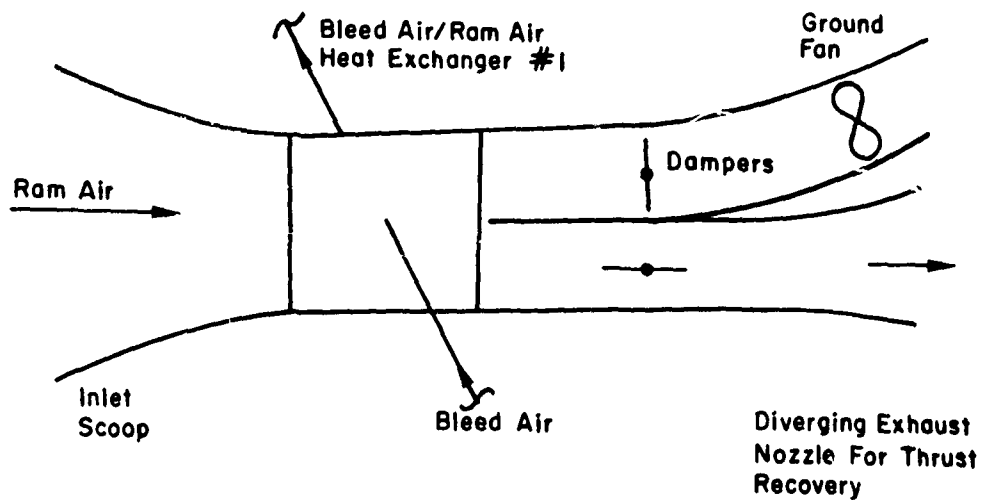


Figure 17. Low Drag, Ram Air Subsystem

scoop at the relative speed of the aircraft and was slowed down to a very low velocity. Then, the air flowed through Heat Exchanger Number 1 and expanded through a diverging nozzle to Mach 1 speed. For this condition, the total drag is less with a nozzle than without it. For Mach 1 operation, the ram air pressure was low and the expansion of the air through the nozzle resulted in a lower velocity than Mach 3 operation. The total drag was approximately the same with or without the nozzle. For ground operation, the air by-passed the nozzle.

(8). Compartment Air Cooled Wall Subsystem

The air cooled compartment consisted of thermal insulation, compartment wall, and air passage between the thermal insulation and compartment wall as shown in Figure 3. The thermal insulation is four inches thick and made of a silicone type fiber material that weighed 0.6 lb/ft³ and has a conductivity of 0.0317 Btu/hr-ft-°F at 275°F (Reference 4).

b. Operation Of The Bootstrap Air Cycle Environmental Control System

The environmental control system was designed to operate for three different conditions as shown in Figures 11 and 18. At Mach 3 condition, a small percentage of engine compressor air was taken from a high pressure compressor stage through a pressure regulator and flow control valve. The bleed air was cooled through Heat Exchangers Numbers 1 through 3 before it entered the bootstrap compressor. The air out of the bootstrap compressor was cooled through Heat Exchanger Number 4 and then expanded through the cooling turbine. The ram air out of Heat Exchanger Number 1 was exhausted through an expansion nozzle at Mach 1 speed as shown in Figure 17. Since this flight condition was for high altitude and dry air, the air going through the water separator produced no ice on the coalescent sock. The cold air was mixed at Point 2 (Figure 18) with the bootstrap compressor discharge air from Point 4 so that a desirable inlet temperature to the compartment was obtained. The air was vented out of the compartment through the cooling wall panels, then through Heat Exchanger Number 2, and finally exhausted overboard.

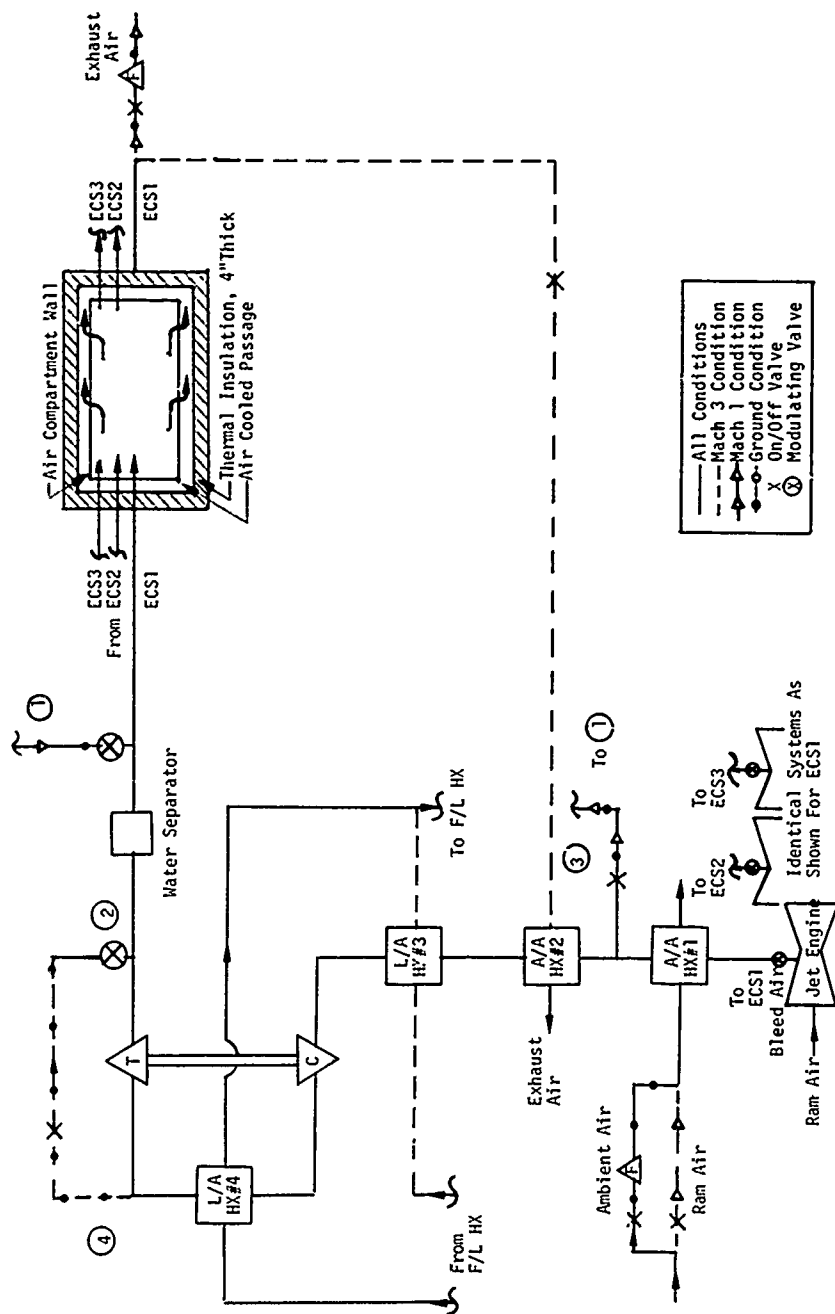


Figure 18. Flow Schematic, bootstrap Air Cycle Environmental Control System With Air Cooled Wall, Operation at all Conditions

For Mach 1 condition, bleed air was taken from the engine compressor and cooled through Heat Exchanger Number 1. The air circulated through Heat Exchangers Numbers 2 and 3 without being cooled since the fluid sink temperatures were not low enough as shown in sample calculations given in Appendix A. The air out of the bootstrap compressor was cooled through Heat Exchanger Number 4 and expended through the cooling turbine. After going through the water separator, the cold air was mixed with the air from Point 1 in order to obtain the required temperature control for the air entering the compartment. The compartment air was exhausted directly overboard, by-passing the cooling panels in the compartment wall and regenerative Heat Exchanger Number 2 because, at Mach 1, aerodynamic heating is much less of a problem as compared to Mach 3 flight.

For the ground condition, the bleed air required for operation of the environmental control system was obtained from the engine compressor when it was operating and from either an auxiliary power unit or ground power cart when the engine was not running. The operation of the environmental control system on the ground was similar to Mach 1 operation except for the following items: The bleed air was cooled initially with ambient air circulated by a ground fan through Heat Exchanger Number 1. For a humid day, the cool air to the water separator had to be maintained above 32°F in order to prevent freezing of the coalescent sock. The air out of the water separator was mixed with bleed air out of Number 1 Heat Exchanger in order to obtain required temperature control for the compartment inlet air.

The heat exchangers, turbine/bootstrap compressor, and compartment cooled wall system were sized for Mach 3 condition. The heat exchangers were sized for the maximum heat load and heat sink temperature and the turbine/bootstrap compressor were sized for the maximum air flow through the turbine. The air cooled compartment wall system was designed for this condition because this was the only case when aerodynamic heating became significant. The ground fans and water separator were sized for ground condition.

c. Operation Of The Semiclosed Bootstrap Air Cycle Environmental Control System

The environmental control system was designed to operate for three different conditions as shown in Figure 19. The operation of the environmental control system for each flight condition was similar to the bootstrap air cycle environmental control system except for the recirculation loop as described in Paragraph II-3a8 and the temperature and flow control for the air entering the compartment. For Mach 3 and Mach 1 conditions, fifty percent of the exhaust air was recirculated. For Mach 3 condition, the turbine exhaust air was mixed with the recirculation air at Point 2 in order to obtain desirable temperatures for the compartment. For Mach 1 condition, the turbine exhaust air was mixed with bootstrap air (from Point 3) at Point 1 and then mixed with recirculation air at Point 2. For ground condition, the turbine exhaust air was mixed with bleed air bypassed at Point 3 to prevent water freezing in the water separator's coalescent sock and then mixed with recirculation air down stream of the water separator for compartment temperature control.

4. DESCRIPTION OF THE VAPOR CYCLE ENVIRONMENTAL CONTROL SYSTEM

In this section, the description of the semiclosed vapor cycle environmental control system with (1) air cooled compartment wall (Figure 7, Cycle V-1), (2) liquid cooled compartment wall (Figure 8, Cycle V-2), (3) liquid cooled wall without a water boiler (Figure 9, Cycle V-3), were given. The components and subsystems are described in Paragraph II-4a and the operation of the cycles are explained in Paragraphs II-4b and 4c.

All of the vapor cycle environmental control systems provided the same ventilation rate of 20 cfm of air per passenger into the compartment and each cycle had the same pressure-enthalpy relation as shown in Figures 20 and 21.

a. Description Of Vapor Cycle Components And Subsystems

The following descriptions are given: (1) in Paragraphs II-4a(1) through II-4a(7) basic components applied to all types of vapor cycle

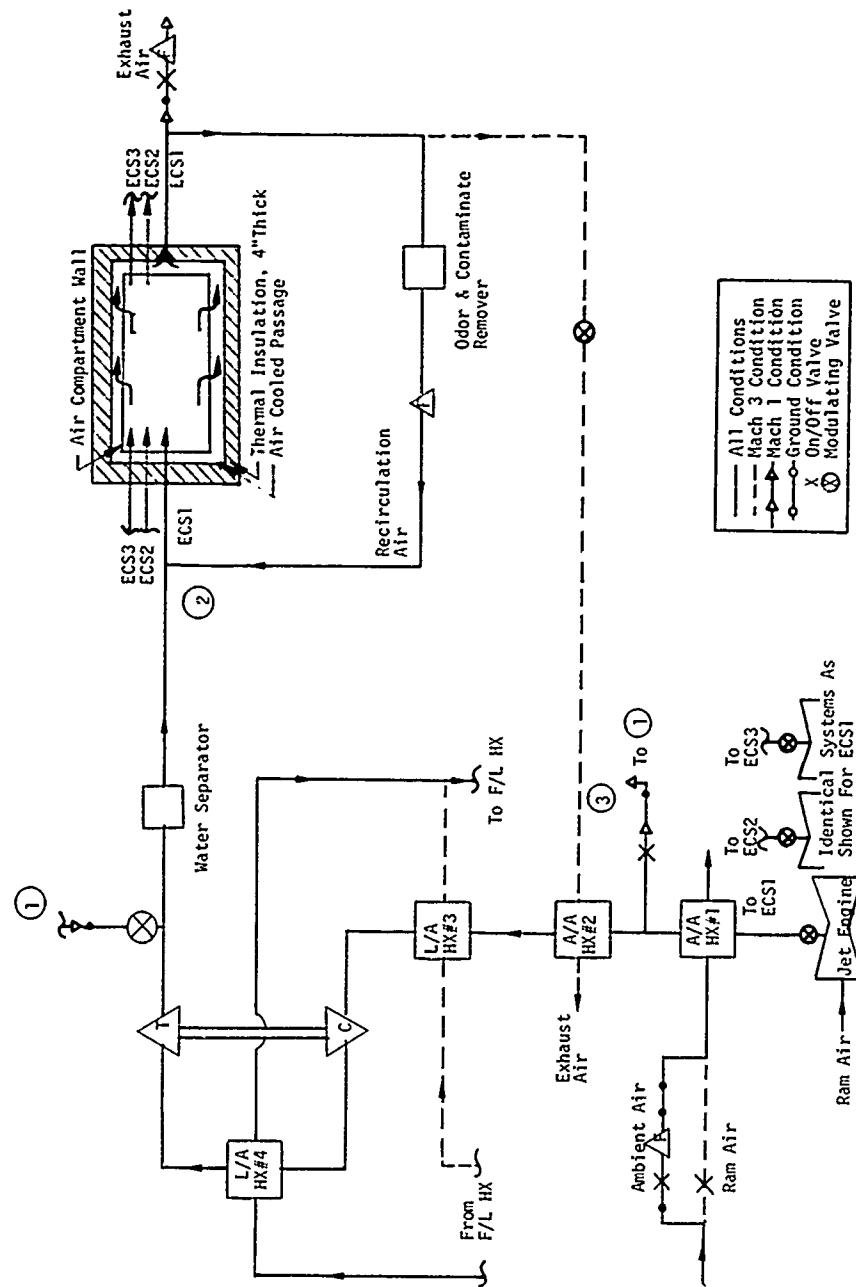


Figure 19. Flow Schematic, Semiclosed Bootstrap Air Cycle Environmental Control System with Air Cooled Wall, Operation at all Conditions

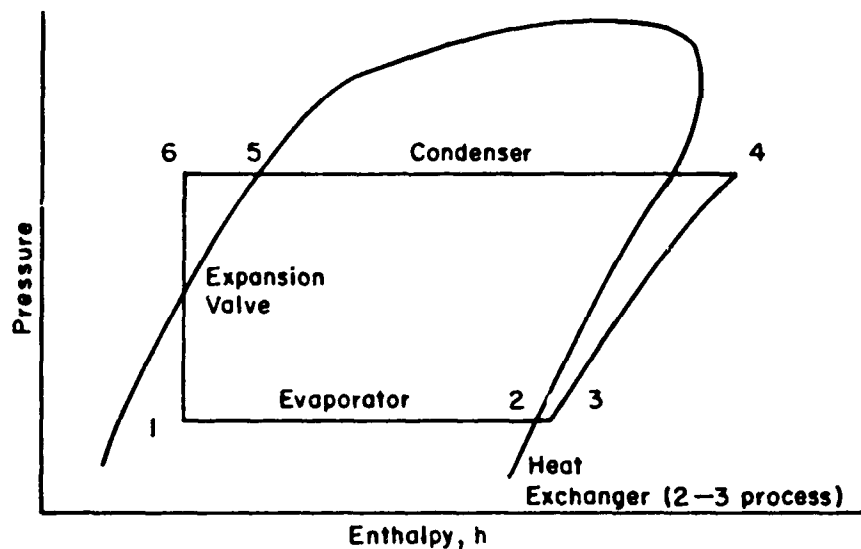


Figure 20. P-H Diagram of a Theoretical Single-Stage Vapor Compression Cycle

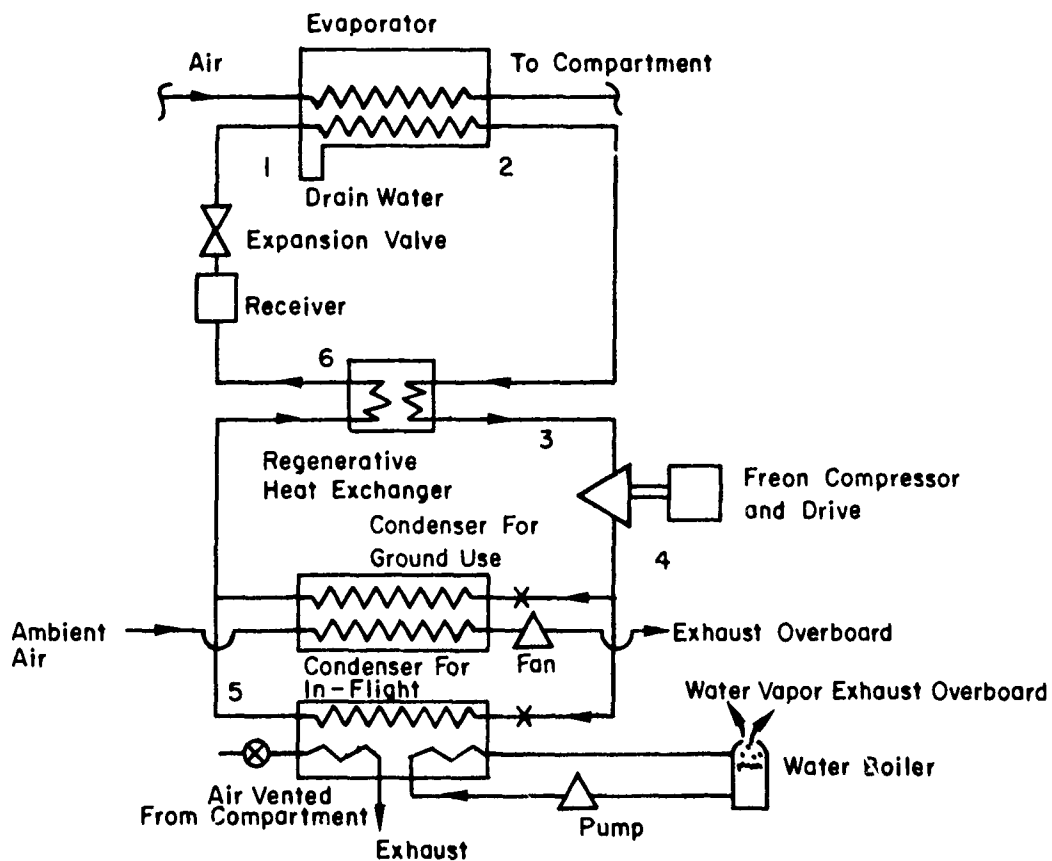


Figure 21. Vapor Cycle System

environmental control systems, (2) in Paragraphs II-4a(8) through II-4a(10), the other components, and (3) in Paragraphs II-4a(11) through II-4a(13) the subsystems.

(1). Compressors

The Freon compressor selected was a centrifugal type similar to the unit used on the United States Air Force XB-70 aircraft (Reference 5). A two stage compressor was required for a high overall pressure ratio output. Surging of the compressor was prevented by bypassing flow around the compressor and maintaining approximately equal flow for all conditions.

The air compressor used in the recirculation loop was an axial, one stage type compressor.

(2). Air/Freon Evaporator

The evaporator selected was a dry type since the refrigerant covering the heat exchanger was in a two phase condition, whereas with the flood type, the refrigerant covering the heat exchanger is in the liquid condition, resulting in a heavier evaporator. The dry type evaporator had a plate/fin core with the refrigerant and air in cross-flow as shown in Figure 22. The plate/fin core was selected because it was more compact and had a lower refrigerant side pressure drop than other cores considered.

(3). Freon/Freon Regenerative Heat Exchanger

The regenerative heat exchanger had a plate/fin core and was used to insure that the refrigerant entering the compressor was in a superheated condition. Otherwise, liquid Freon could damage the blades of the compressor.

(4). Liquid/Air Heat Exchanger

The liquid/air heat exchanger had a tube/fin core similar to the one described in Paragraph II-3a(2).

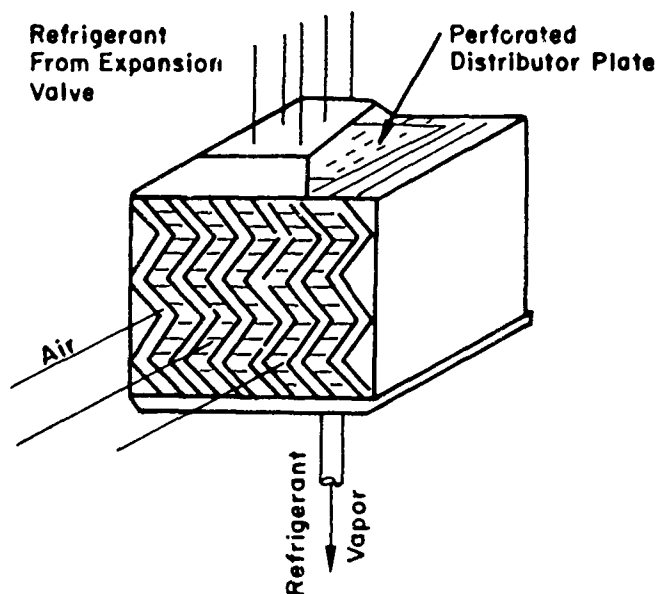


Figure 22. Single Pass Plate/Fin Evaporator

(5). Ground Fan

A two stage axial flow type fan was selected to circulate ambient air through the ground condenser for ground condition.

(6). Ground Condenser

The ground condenser had a plate/fin core similar to the air/Freon evaporator. The heat sink was ambient air, using a fan to circulate air through the core.

(7). Odor and Contaminate Remover

The odor and contaminate remover was of the same type as described in Paragraph II-3a(4).

(8). Resistance Heater

The resistance heater was used to heat the air out of the evaporator to maintain a desirable temperature level when the air was below a

specified temperature. Construction of resistance heaters (electric heaters) consisted of a finned heat transfer surface on the air side and resistance material coating on the element plates. Protection from overheating was provided by thermal protector for each heater element. Figure 23 illustrates a typical resistance heater construction.

(9). Flight Condenser

The flight condenser selected for Cycles V-1 and V-2 had a plate/fin geometry with cross-flow arrangement as shown in Figure 24 for Freon, exhaust air, and water. The water boiler and flight condenser arrangement is shown in Figure 25. The exhaust air temperature was raised to the Freon condensing temperature. The water boiled in the condenser and was expended overboard through the exhaust pressure regulator. By adjusting the pressure regulator, the water temperature was controlled to 15°F below the Freon temperature.

The flight condenser for Cycle V-3 had a tube/fin core geometry with the Freon circulated through the tubes.

(10). Liquid/Freon Evaporator

The liquid/Freon evaporator, for Cycles V-2 and V-3, had a tube/fin core geometry with Freon circulating through the tubes. The cooling liquid circulated through the compartment tube/fin cooled wall for Mach 3 condition as shown in Figure 10.

(11). Transport Liquid Loop Subsystem

The transport liquid loop for Cycles V-1 and V-2 is shown in Figure 26; and for Cycle V-3, in Figure 27.

(12). Compartment Liquid Cooled Wall Subsystem

The liquid cooled wall used in the Cycle V-2 consisted of thermal insulation, compartment wall, and a tube/fin aluminum heat exchanger between the insulation and wall as shown in Figure 10. The thermal

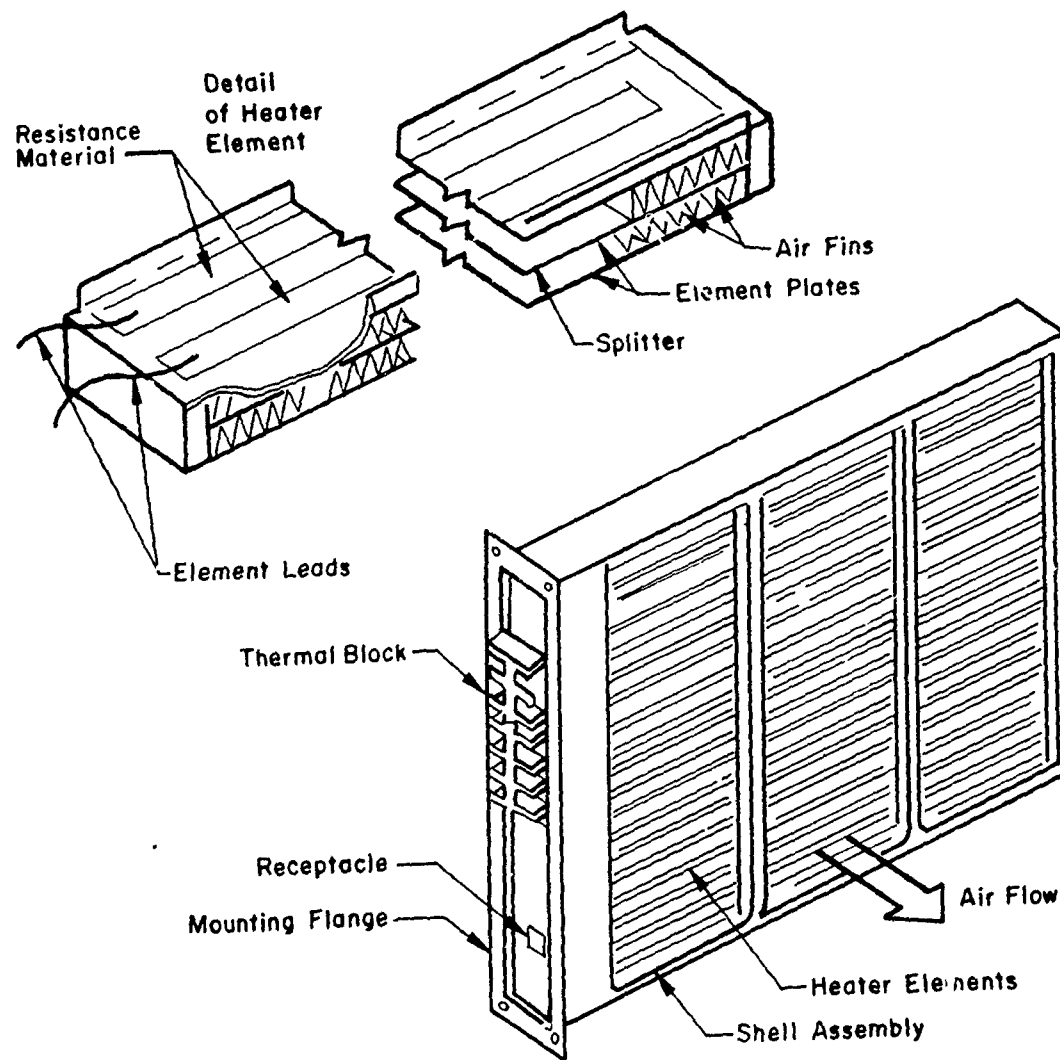


Figure 23. Typical Resistance Heater

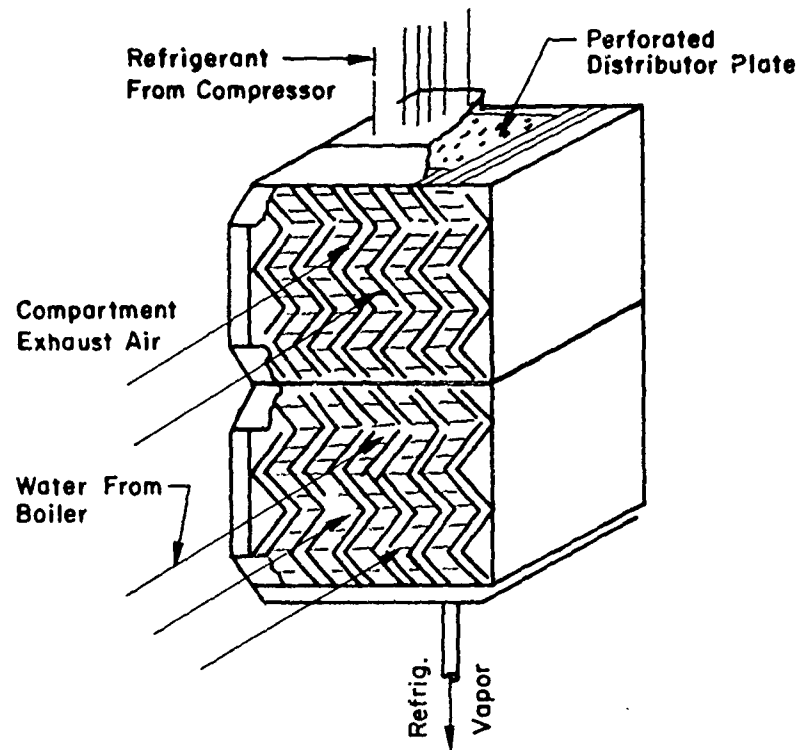


Figure 24. Air Water/Freon Condenser

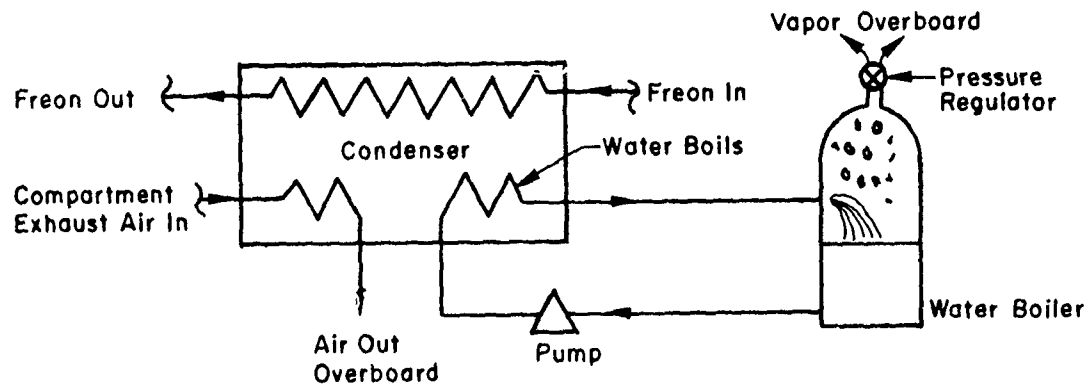


Figure 25. Condenser and Water Boiler

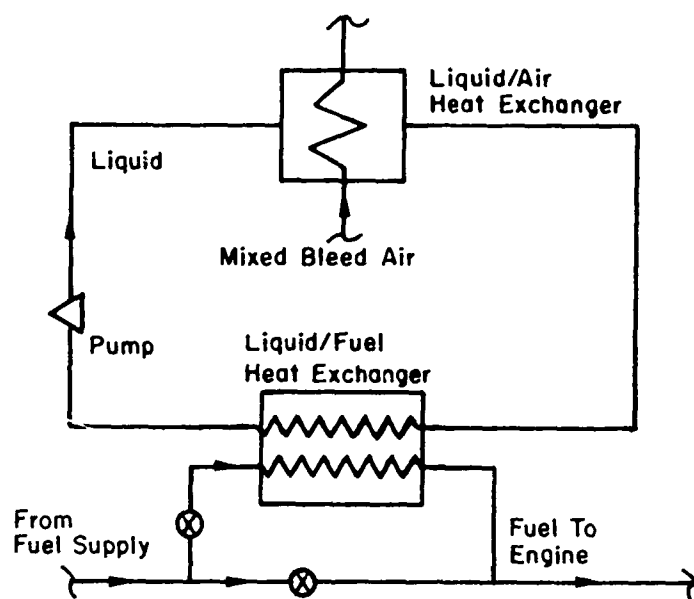


Figure 26. Transport Liquid Loop Subsystem Without Liquid/Freon Condenser (Used in Cycles V-1 and V-2)

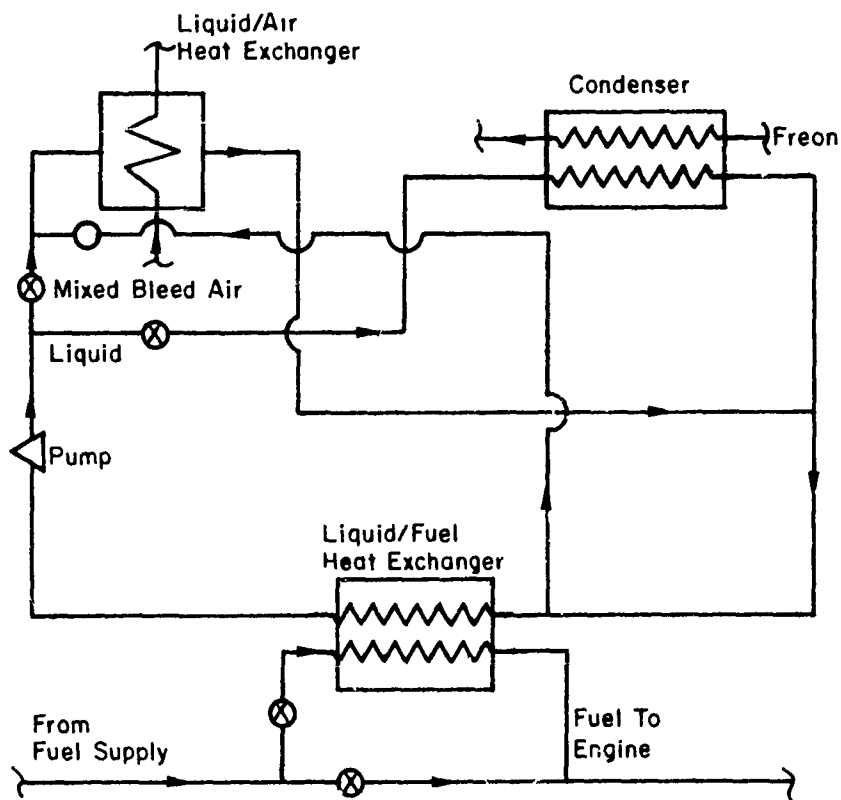


Figure 27. Transport Liquid Loop Subsystem with Liquid/Freon Condenser (Used in Cycle V-3)

insulation was two inches thick and was made of silicone type fiber material that weighed 0.6 lb/ft^3 and had a conductivity of $0.0317 \text{ Btu/hr-ft-}^\circ\text{F}$ at 275°F (Reference 4).

(13). Compartment Air Cooled Wall Subsystem

The air cooled wall used in the Cycle V-1 was of the same type as the one described in Paragraph II-3a(8) for the air cycle environmental control system.

b. Operation Of The Vapor Cycle Environmental Control System With Air Cooled Wall

This vapor cycle environmental control system was designed to operate for three different flight conditions as shown in Figures 11 and 28. For Mach 3 condition and starting at Point 1 (Figure 28), the bleed air and an equal amount of recirculated air from the compartment exhaust air was mixed and circulated through the liquid/air heat exchanger to be cooled. The air passed through the air/Freon evaporator where it was cooled to a temperature that was desirable for compartment cooling. The compartment air was vented through the cooling air passages in the compartment wall and exhausted where it was divided equally going to the odor/contaminate remover and flight condenser. The condenser was cooled by the exhaust air and water, which boiled into the condenser and was exhausted overboard as shown in Figure 25.

The vapor cycle subsystem consisted of the compressor, evaporator, condenser, and regenerative heat exchanger. Freon 11 was selected because it was nontoxic, odorless, and nonflammable. The compressor was designed to run at maximum flow without any bypass flow around the compressor. The heat load to the condenser was rejected to the air and water as illustrated in Figure 25.

For Mach 1 condition, the operation of the environmental control system was similar to Mach 3 condition except for the fact that the exhausted compartment air was not heated in the compartment wall passages since no aerodynamic heating occurred.

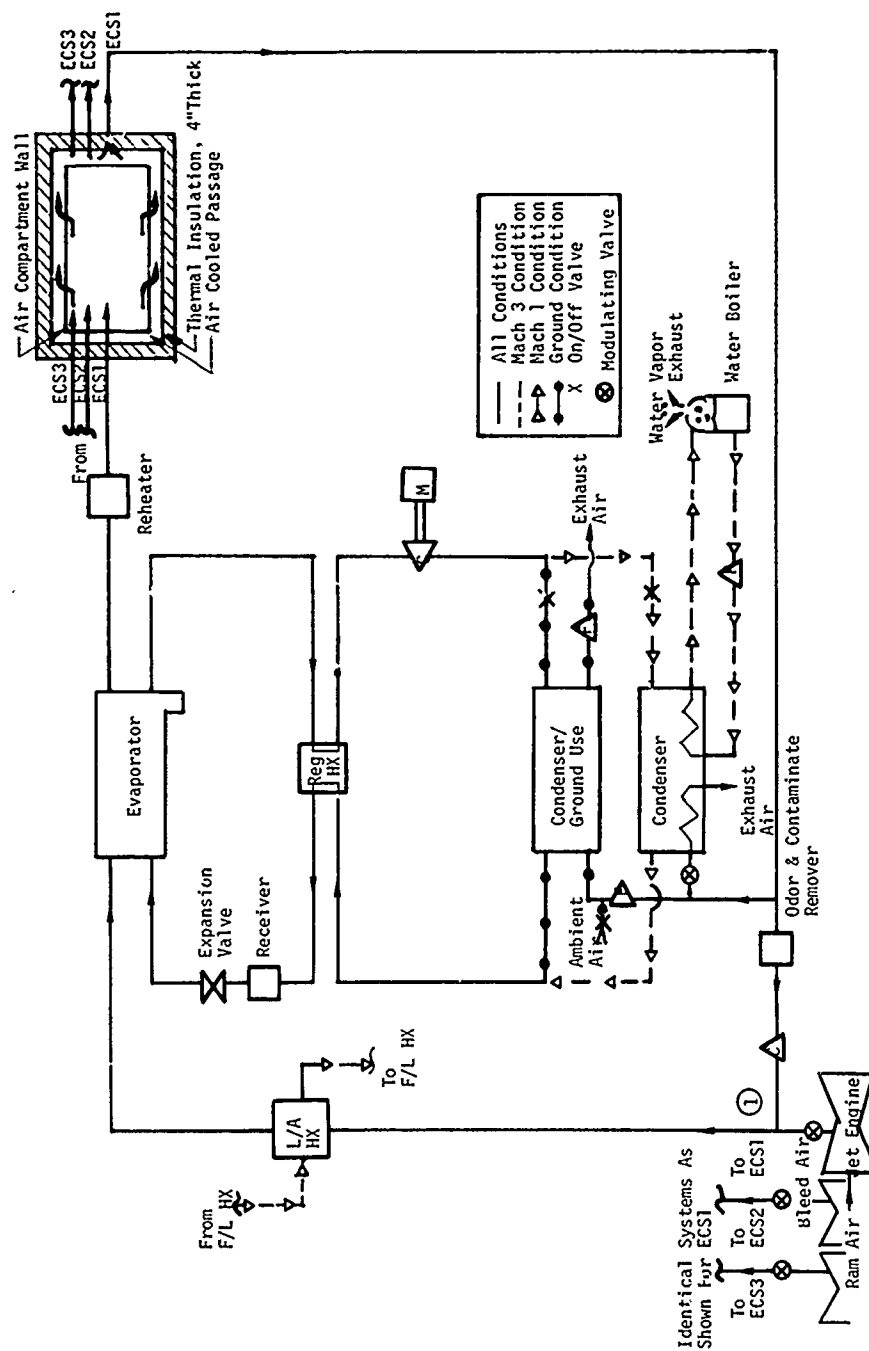


Figure 28. Flow Schematic, Semiclosed Vapor Cycle Environmental Control System with Air Cooled Wall, Operation at all Conditions

For the ground condition, the operation was the same as Mach 1 condition except for the following differences: the liquid/air heat exchanger was not required for cooling the bleed air and the ground condenser was used instead of the flight condenser.

The liquid/air heat exchanger, air/Freon evaporator, air/Freon condenser, Freon compressor, and air cooled compartment wall were sized and designed for Mach 3 condition. The liquid/air heat exchanger was sized for this condition since the heat load was maximum. The evaporator and flight condenser were sized for this condition because the inlet air temperature of the evaporator and Freon flow were maximum. The compressor was sized for maximum flow and the value of flow was determined by the flight condition of maximum cooling load which was at Mach 3 condition. The air cooled compartment wall was also designed for this condition because this was the only case when aerodynamic heat was significant.

c. Operation Of The Vapor Cycle Environmental Control System With Liquid Cooled Wall

The operation of the vapor cycle environmental control system was the same as the preceding Cycle V-1 operation except a liquid cooled wall was used in place of an air cooled wall and an additional evaporator was used as shown in Figure 29. For Mach 3 condition, the transport liquid circulated through the compartment cooling wall passages and the liquid/air evaporator. The air that was cooled through the air/Freon evaporator went through the compartment and was exhausted, where part of it went through the flight condenser and part of it was recirculated. For Mach 1 and ground conditions, the operation of the environmental control system was the same as Cycle V-1 as shown in Figure 28. The liquid cooled wall was designed for Mach 3 condition since this was the only case when aerodynamic heat was significant. The liquid/Freon evaporator was sized for Mach 3 condition since the cooling load was maximum. All the other components were sized for this same condition as the preceding Cycle V-1 analysis in Paragraph II-4b.

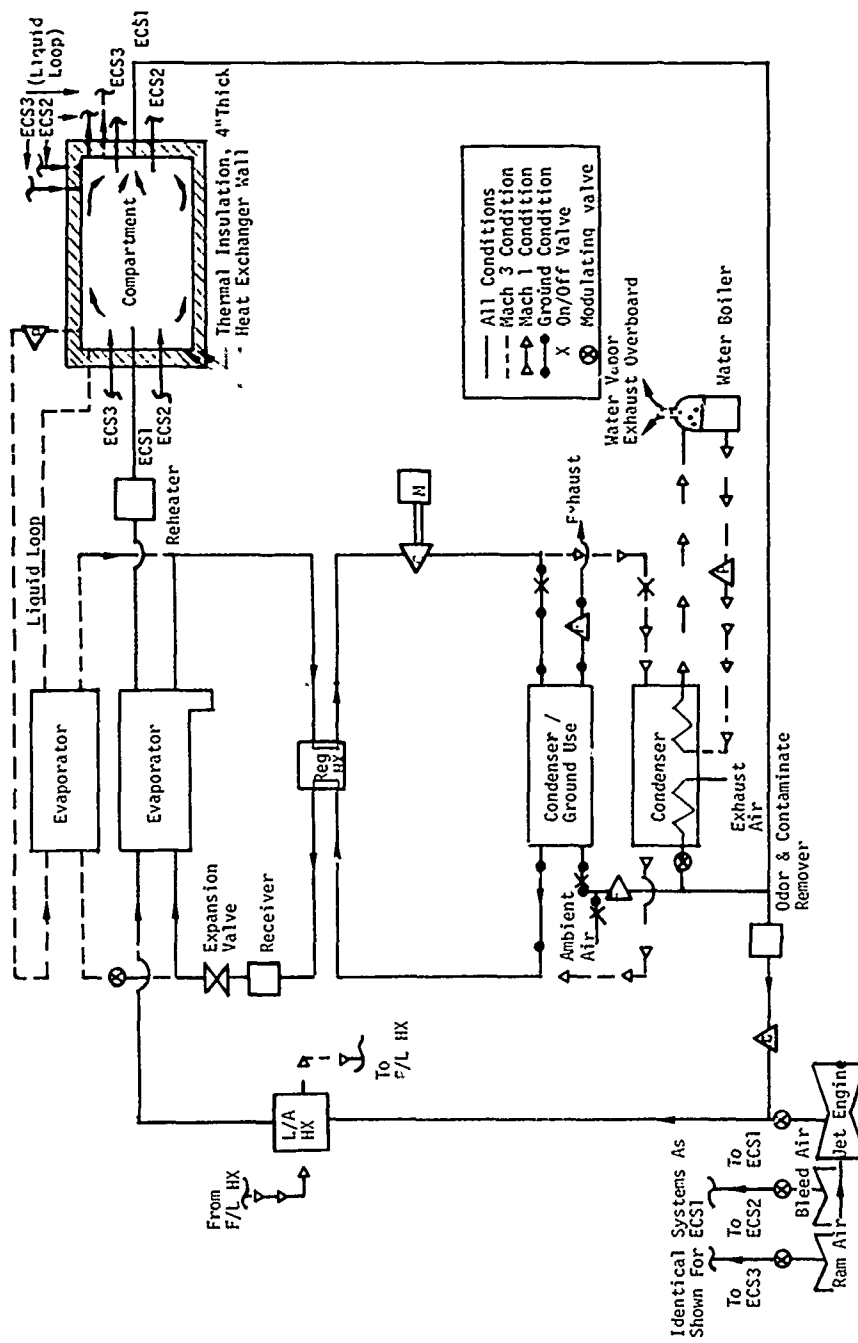


Figure 29. Flow Schematic, Semiclosed Vapor Cycle Environmental Control System with Liquid Cooled Wall, Operation at all Conditions

d. Operation Of The Vapor Cycle Environmental Control System With Liquid Cooled Wall/Without Water Boiler

The operation of the vapor cycle environmental control system with the liquid cooled wall and without a water boiler was the same as the preceding Cycle V-2 operation except precooled fuel was used to cool the Freon in the flight condenser and exhaust air was used to cool the bleed air in an air/air regenerative heat exchanger as shown in Figure 30. The advantage of this system was that water was not used as a heat sink, therefore, the expendable penalty was zero. Where as in Cycles V-1 and V-2, the expendable penalty was large because water was boiled overboard. For Mach 3 condition, the bleed air and recirculated air were mixed, then cooled through the air/air regenerative heat exchanger, liquid/air heat exchanger, and air/Freon evaporator. After the air was exhausted out of the compartment, part of the air was circulated through the regenerative heat exchanger and part of it was recirculated through the environmental control system. For Mach 1 condition, the mixed bleed air and recirculated air was circulated and cooled through the regenerative heat exchanger. The mixed air went through the liquid/air heat exchanger but cooling was not accomplished since the heat sink fluid temperature was higher than the air entering the heat exchanger. The liquid/Freon evaporator was not needed for cooling at this condition. The other components operated similarly to the operation at Mach 3 condition. For the ground condition, the operation of the environmental control system was similar to the other vapor cycle environmental control systems operating at ground condition except for the ground condenser. For this cycle, the heat sink fluid was entirely ambient air. The regenerative heat exchanger and flight condenser were sized for Mach 3 condition and the ground condenser was sized for ground condition. All other components were sized for the same conditions as similar components in the other vapor cycle environmental control systems.

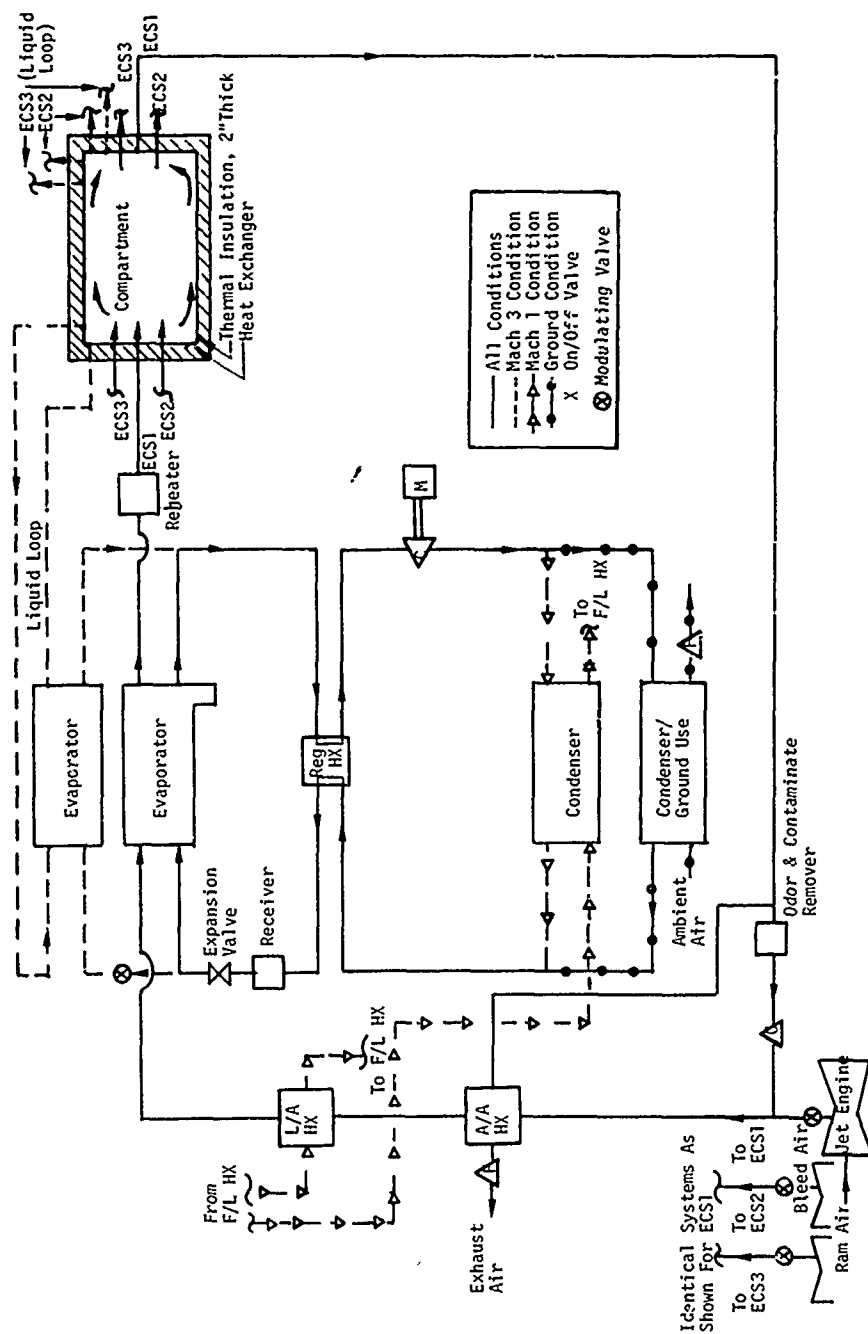


Figure 30. Flow Schematic, Semiclosed Vapor Cycle Environmental Control System with Liquid Cooled Wall, Without Water Boiler, Operation at all Conditions

SECTION III

ENVIRONMENTAL CONTROL SYSTEM WEIGHT AND COMPONENT ANALYSIS

1. INTRODUCTION

The analysis in this Section is presented in the following order: First, the definition of the total weight penalty is derived for each type of environmental control system under consideration or selected. The environmental conditions are then formulated for ambient, ram, and bleed air. Finally, the component analysis is established and this information is used later to determine performance and weight penalty.

2. DEFINITION OF THE SYSTEM WEIGHT PENALTY

The incorporation of an air conditioning system into an aircraft affects aircraft performance by the imposition of additional weight, drag, and power consumption. The additional weight is contributed by the dead weight of the air conditioning equipment. Additional drag results from momentum drag caused by ram air taken on board for cooling or pressurization. Additional power consumption arises for the shaft power and/or bleed air requirements of the air conditioning system. The additional drag and power consumption can be expressed in terms of the extra amount of fuel that has to be carried to maintain the same range as compared to the same airplane without a cooling system. The weight penalty evaluation is based on extra fuel load and total weight of each ECS.

Certain parameters must be given or assumed for the flight profile in order to make a reasonable penalty evaluation. The information needed is the following:

- a. A typical flight profile including data on Mach number, altitude, free stream temperature, and engine power setting as a function of flight duration.
- b. Engine data, including compressor pressure ratio, bleed air temperature and pressure, and specific fuel consumption as a function of altitudes, power setting, and Mach number.

- c. Lift to drag ratio of the airplane at take-off and at the beginning of each flight phase.
- d. Required ram air flow, drag equivalent of bleed air extraction, and/or drag equivalent of shaft power extraction for each cooling system during each of the separate flight phases.

3. STEPWISE INTEGRATION METHOD (Reference 6)

The weight penalty evaluation used in this study is carried out by the Stepwise Integration Method. This method approximates the actual flight mission with a series of steps which are integrated to obtain the total penalty expressed in take-off weight. The system which yields the minimum take-off weight represents the optimum design of those considered. For each step, the penalties due to system fixed weight, W_{TS} , expendable fluid, W_{Te} , ram air flow, W_{Tr} , bleed air flow, W_{Tb} , and shaft horsepower, W_{hp} , can be determined in terms of the take-off weight and the derivations are presented in the following sections. The total penalty, Pl_T , is the sum of the individual penalties indicated above.

a. Fixed Weight Penalty (W_{TS})

The fixed weight penalty, W_{TS} in lb, is defined as the fixed weight of the environmental control system components, W_s in lb, and the amount of fuel expended by the airplane in carrying the fixed weight, W_{fs} in lb, for a time interval k . At the start of the flight, $k=0$, W_{TS_0} is equal to the fixed weight W_s plus the total fuel needed by the aircraft in carrying the fixed weight, W_{fs_0} . At the end of the flight, $k=n$ or n steps later, the fixed weight penalty is the fixed weight W_s , with all the fuel already expended in carrying the fixed weight and therefore $W_{fs_n} = 0$. For a finite time change, $t_{k+1} - t_k$, the fixed weight penalty is decreased by the fuel expended in carrying the fixed weight and is (Reference 6):

$$W_{TS_{k+1}} - W_{TS_k} = -(t_{k+1} - t_k) [W_{TS}(sfc/L/D)]_{t_k} \quad (1)$$

where k is the interval index, $t_k = 1/2 (t_{k+1} - t_k)$, L/D is the lift to drag ratio, and sfc is the thrust specific fuel consumption in lb fuel per lb thrust per hour.

Equation 1 can also be expressed in the differential form as

$$dW_{TS}/dt + a W_{TS} = 0 \quad (2)$$

where $a = sfc/(L/D)$ and by integrating Equation 2 it yields

$$W_{TS_0} = W_s \exp \left(\sum_{i=1}^n a_i (t_i - t_{i-1}) \right) \quad (3)$$

where i is a flight segment index, t_{i-1} is the beginning of a flight segment and t_i is the end of a flight segment, and n is the flight segment index indicating the end of the overall flight, and 0 is a flight segment index indicating the beginning of the flight. The detailed derivation of Equation 3 is given in Appendix B and the assumed flight profile for the Mach 3 troop transport aircraft under study is given in Figure 11.

From Equation 3 the total fuel expended in carrying the fixed weight can be determined to be

$$W_{fs_0} = W_{TS_0} - W_s$$

b. Ram Air Penalty (W_{Tr})

Outside air which is taken aboard as ram air through a heat exchanger is slowed down and pressurized (diffuser action), representing a ram air drag penalty. Part of the ram air drag penalty can be eliminated by expanding the pressurized air through a nozzle as shown in Figure 17. The penalty is defined as the fuel that is expended in the engine so that the additional amount of thrust produced will offset the drag loss, W'_{fr} in lb, plus the extra fuel, W_{fr} in lb, expended in carrying the

fuel \dot{W}'_{fr} up to the point where it is expended in the engine. For a finite time change, the difference in ram air penalty is (Reference 6)

$$\begin{aligned} W_{Tr_{k+1}} - W_{Tr_k} = & -[W_{Tr}(sfc/L/D)]_{t_k} (t_{k+1} - t_k) \\ & - \dot{W}'_{fr} (t_{k+1} - t_k) \end{aligned} \quad (4)$$

where k is an interval index and \dot{W}'_{fr} is a constant fuel flow rate expended in the engine to overcome the ram air drag in lb/hr and equal to $\dot{W}'_{fr} / (t_{k+1} - t_k)$.

Equation 4 can be expressed in the differential form as

$$dW_{Tr}/dt + a W_{Tr} + \dot{W}'_{fr} = 0 \quad (5)$$

Upon integration (detailed derivation is given in Appendix B),

$$W_{Tr_0} = \sum_{i=1}^n \left(\dot{W}'_{fr_i} \frac{(e^{x_{i-1}})}{a_i} \exp \left(\sum_{j=1}^{i-1} x_j \right) \right) \quad (6)$$

where both i and j are the same flight segment index, W_{Tr_0} is the weight of the fuel expended for the total flight due to the ram air penalty and is the weight of the fuel required at the beginning of the flight, $x_i = a_i(t_i - t_{i-1})$, and $x_j = a_j(t_j - t_{j-1})$. Then the term \dot{W}'_{fr} is defined as:

$$\dot{W}'_{fr_0} = W_{Tr_0} - \sum_{k=1}^n \dot{W}'_{fr_k}$$

The fuel expended \dot{W}'_{fr_i} is determined in the following terms:

By integrating Newton's Law, $F = m du/dt$, the drag is

$$\Gamma h_r = \dot{W}'_r (u_r - u_{rho}) / (60 g) \quad (7)$$

Where g is the gravitational acceleration in ft/sec^2 , u_r is the ram air velocity in ft/sec , u_{rho} is the exhaust air velocity through the nozzle in ft/sec , and \dot{W}_r is the ram air flow through the heat exchanger in lb/min . Since

$$\dot{W}'_{fr} = \text{sfc} (Th_r)/60 \quad (8)$$

From Equations 7 and 8,

$$\dot{W}'_{fr} = \dot{W}_r (\text{sfc}) (u_r - u_{rho})/3600 g \quad (9)$$

Substituting Equation 9 into Equation 6, the weight of the fuel expended for the total flight due to the ram air penalty is obtained:

$$W_{tr0} = \left[\sum_{i=1}^n \left(\text{sfc}_i (u_r - u_{rho}) (\dot{W}_{r_i}) (t_i - t_{i-1}) / (3600 g) \right) \left(\frac{e^{x_{i-1}}}{x_i} \left(\exp \left(\sum_{j=1}^i x_j \right) x_j \right) \right) \right] \quad (10)$$

c. Expendable Weight Penalty (W_{Te})

The expendable weight penalty, W_{Te} , results from a liquid being carried to be used as an expendable coolant in an environmental control system. In this project, the only expendable coolant examined will be water used as a heat sink for the condenser in a vapor cycle system as shown in Figure 25.

The expendable weight penalty is composed of the expendable weight, W_e , and the fuel expended, W_{fe} , in carrying the weight of water, both of which will be constantly changing. For a time interval k , let W_{fe0} equal the fuel expended for the total flight due to the total weight of the expendable water, W_{e0} . At the beginning of the flight ($k=0$),

$$W_{Te0} = W_{e0} + W_{fe0}$$

and at the end of the flight ($k=n$), $W_{Te_n} = 0$. Fuel is expended in carrying the expendable water and fuel up to the point when the water is fully expended. Then the differential form representing the decrease in weight is

$$dW_{Te}/dt + W_{Te} (sfc/(L/D)) + \dot{W}_e = 0 \quad (11)$$

where \dot{W}_e is the expendable coolant flow rate in lb/hr.

As in the case of ram air penalty, the flight is divided into n segments and similar equations derived. The total expendable weight penalty is:

$$W_{Te_0} = \sum_{i=1}^n \left[\left(\dot{W}_{e_i} (t_i - t_{i-1}) \right) [(e^{x_{i-1}})/x_i] \exp \sum_{j=1}^{i-1} x_j \right] \quad (12)$$

d. Bleed Air Penalty (W_{Tb})

The bleed air penalty results from that part of ram air being pressurized in the engine compressor, which does not enter the combustion chamber and turbine to produce useful work and thus involves a power loss in terms of engine fuel expended. The bleed air is conditioned in both the air cycle and vapor cycle and is used as compartment cooling air.

The bleed air penalty is derived for the ram air penalty in terms of fuel expended and engine compressor loss in terms of horsepower penalty due to a portion of the engine air being tapped off a compressor stage to be used in the environmental control system. Again the flight is divided into n segments and similar equations derived as in Section 3-3b. The bleed air weight penalty is:

$$W_{Tb_0} = \sum_{i=1}^n \left[\left((\dot{W}_{fb} + \dot{W}_{frb_i}) (t_i - t_{i-1}) \right) [(e^{x_{i-1}})/x_i] \exp \sum_{j=1}^{i-1} x_j \right] \quad (13)$$

where W_{Tb0} is the weight of the fuel expended for the total flight due to the engine compressor penalty in lb, \dot{W}_{frb} is the constant fuel flow rate expended due to the ram air drag in lb/hr and similar to \dot{W}'_{fr} , \dot{W}_{fb} is the constant fuel flow rate expended due to the horsepower penalty in lb/hr, and \dot{W}_b is the flow rate of the engine bleed air in lb/min. The fuel expended, \dot{W}_{frb_i} , is determined in a similar manner as \dot{W}_{fr_i} . Then

$$\dot{W}_{frb_i} = (\text{sfc } \dot{W}_b u_r)_i / (3600 \text{ g}) \quad (14)$$

The fuel expended \dot{W}_{fb} is determined in terms of horsepower penalty and can be defined as

$$\dot{W}_{fb} = (\text{sfc}') (H_{p_{ec}}) \quad (15)$$

where $H_{p_{ec}}$ is the horsepower loss due to a portion of the engine air being tapped off a compressor stage to be used in the environmental control system and sfc' is the engine horsepower specific consumption in lb/(hp-hr).

The horsepower is the energy required to raise a given mass flow to a specific heat per unit of time and is expressed as

$$H_{p_{ec}} = (\rho \dot{V} H_{ec}) (550 \eta_{ec}) \quad (16)$$

where H_{ec} is the isentropic heat for the engine compressor in feet, ρ is the specific density in lb/ft³, \dot{V} is the volumetric flow in ft³/min, η_{ec} is the adiabatic efficiency of the engine compressor. Since $\dot{W}_b = \rho \dot{V}$, Equation 16 can be rearranged as

$$H_{p_{ec}} = \dot{W}_b H_{ec} / (550 \eta_{ec}) \quad (17)$$

The isentropic heat is:

$$H_{ec} = 778 c_p T_r [(P_{ec}/P_r)^{(\gamma-1)/\gamma} - 1] \quad (18)$$

where c_p is the specific heat of air in Btu/(lb-°R), T_r is the ram air total temperature in °R, P_{ec} is the bleed air total pressure tapped off a certain engine compressor in psia, P_r is the ram air total pressure in psia, and γ is the ratio of specific heats, c_p/c_v . Since

$$T'_{ec}/T_r = (P_{ec}/P_r)^{(\gamma-1)/\gamma}$$

for an isentropic process where T'_{ec} is the theoretical total temperature of the bleed air off the desired stage of the engine compressor °R, then

$$H_{ec} = c_p (T'_{ec} - T_r) \quad (19)$$

$$\text{Let} \quad \Delta T_{ec} = (T'_{ec} - T_r)$$

$$\text{then} \quad H_{ec} = c_p (\Delta T_{ec}) \quad (20)$$

$$\text{and} \quad H_{p_{ec}} = \dot{W}_b c_p \Delta T_{ec} / (550 \eta_{ec}) \quad (21)$$

By substituting Equations 21 and 9 into Equation 13 the total bleed air penalty W_{Tb0} can thus be defined as

$$W_{Tb0} = \sum_{i=1}^n \left[\frac{[H_{p_{ec}} (sfc_i + sfc'_i)] (t_i - t_{i-1})}{([e^{x_i-1}]/x_i) \exp \sum_{j=1}^{i-1} x_j} \right] \quad (22)$$

e. Shaft Horsepower Penalty (W_{hp})

The shaft horsepower penalty results from energy being extracted from the engine gearbox to drive the components of an environmental control system. The shaft-driven Freon compressor and fan are examples of such components used in an environmental control system.

The shaft horsepower penalty is derived in a similar manner as the bleed air penalty except that the \dot{W}_{fb} term as described by Equation 15 is replaced by \dot{W}_{fh} , the constant fuel rate expended due to horsepower penalty in lb/hr.

$$\dot{W}_{fh} = \text{sfc}' \text{ Hp}_s \quad (23)$$

where Hp_s is the shaft horsepower required to operate an environmental system component. The total shaft horsepower penalty is similar to Equation 22 but without the drag term

$$W_{hp_o} = \sum_{i=1}^n \left[\frac{[\text{sfc}'_i \text{ Hp}_{s_i}] (t_i - t_{i-1})}{([e^{x_i} - 1]/x_i) \exp \sum_{j=1}^{i-1} x_j} \right] \quad (24)$$

where W_{hp_o} is the weight of the fuel expended for the total flight due to the Hp requirement.

4. ENVIRONMENTAL CONDITIONS

In this subsection a summary of the various data and derivations are presented that are needed in determining the environmental conditions related to the operation of the environmental control system.

a. Ambient Air

The variation of air temperature with altitude is defined by the US Standard Atmosphere, 1962. The standard atmosphere as shown in Reference 7, is a hydrodynamically consistent homogeneous atmosphere, essentially in agreement with the International Civil Aviation Organization (ICAO) Standard Atmosphere of 1954. The density of air for a standard day is 0.07648 lb/ft^3 at sea level and 59°F .

b. Ram Air (Reference 8)

For high speed aircraft, the ram air total temperature and pressure are much greater than the ambient conditions. In actual practice the ram air temperature will be close to the theoretical amount given by the equation

$$T_r = T_a \left(1 + \frac{\gamma - 1}{2} M^2 \right) \quad (25)$$

where T_a is the ambient air temperature in R, γ is the ratio of c_p to c_v , and M is the flight Mach number. The pressure rise, for isentropic compression, will be

$$P'_r = P_a \left(1 + \frac{\gamma-1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}}$$

where P'_r is the theoretical ram air total pressure in psia and P_a is the ambient air pressure in psia. In practice, for an inlet heat exchanger scoop as shown in Figure 17, the recovery factor, η_r , is assumed to be 0.5 for supersonic speed and 0.75 for subsonic speed. The ram air total pressure, P_r , in psia is

$$P_r = P_a \left(1 + \eta_r \left[\left(1 + \frac{\gamma-1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}} - 1\right]\right) \quad (26)$$

c. Bleed Air

The bleed air, tapped off from a certain engine compressor stage and treated in the environmental control system, is used to ventilate, cool, and pressurize the compartments. The choice of bleed air pressure is based on the type of environmental control system used or selected, cooling requirement, bootstrap turbine exhaust temperature, and efficiency of the bootstrap turbine and compressor. Once the bleed air total pressure, P_b , is determined, the isentropic bleed air total temperature, T_b' , can be determined by isentropic compression relationship

$$T_b'/T_r = (P_b/P_r)^{(\gamma-1)/\gamma} \quad (27)$$

However, the actual process (close to an adiabatic one) will lead to compressor adiabatic efficiency, η_{ec} , defined by

$$\eta_{ec} = \frac{T_r (r_b)^{(\gamma-1)/\gamma} - T_r}{T_b' - T_r} \quad (28)$$

Where r_b is P_b/P_r

5. COMPONENT ANALYSIS

This analysis subsection identifies the major components that are used in the cycle along with some performance characteristics and fixed weight information based on the current state-of-the-art. However, the manner in which these components are arranged can represent an advanced concept.

a. Radial Turbine

The analysis of the turbomachinery is based on the techniques of dimensional analysis as treated by Balje (Reference 9). Balje is able to derive a single generalized relationship between the two key similarity parameters of turbomachinery: specific speed and specific diameter.

The specific speed is defined as

$$N_s = (N_t \dot{V}_t^{1/2}) / H_t^{3/4} \quad (29)$$

Where N_t is the turbine speed in rpm, \dot{V}_t is the turbine outlet flow in ft^3/sec , and H_t is the head available to the turbine in $(\text{ft-lb}_f)/\text{lb}_m$. The total head is the change in specific enthalpy and is defined by

$$H_t = c_p (T_{ti} - T_{to}) \times 778 \frac{\text{ft-lb}_f}{\text{Btu}} \quad (30)$$

where T_{ti} is the turbine inlet total temperature in $^{\circ}\text{R}$ and T_{to} is the turbine total outlet temperature in $^{\circ}\text{R}$.

Assuming the theoretical expansion is isentropic, the turbine exhaust total temperature, T'_{to} is

$$T'_{to} = T_{ti} (P_{to}/P_{ti})^{(\gamma-1)/\gamma} \quad (31)$$

where P_{ti} is the turbine inlet total pressure in psia and P_{to} is the turbine outlet total pressure in psia.

The actual turbine exhaust temperature is

$$T_{to} = T_{ti} - \eta_t (T_{ti} - T_{to}') \quad (32)$$

where η_t is the turbine adiabatic efficiency.

The wheel diameter, in ft, is defined as:

$$D_t = (D_s \dot{V}_t^{1/2}) / H_t^{1/4} \quad (33)$$

and D_s is the specific diameter.

For this project, the single stage radial in-flow turbine is selected since they are commonly employed for aircraft applications. The value of N_s and D_s , assumed in Equations (29) and (33) are 60.0 and 1.7, respectively. With the above equations, the turbine wheel diameter and rpm can be established.

The bootstrap compressor that loads the turbine is assumed to be of the same diameter and the combined weight of turbine and compressor, M_{te} in lb, is taken to be (Reference 8)

$$M_{te} = 100 (D_t)^3 \quad (34)$$

b. Freon Compressor (References 10 and 11)

The Freon compressor, used in aircraft applications, is a centrifugal machine and is designed for a specific speed, N_s , of 60. The tip Mach No. is set to one, a near optimum value for practical compressors. The tip speed, u_{fc} in ft/sec, is

$$u_{fc} = (\gamma g R T_{Co})^{1/2} \quad (35)$$

where R is the gas constant in ft-lb_f/(lb_m-°R) and T_{Co} is the total temperature of the Freon out of the compressor in °R.

The actual head, H_{fc} in ft-lb_f/lb_m, is

$$H_{fc} = (c_p) (\Delta T_{fc}) (\eta_{fc}) (778 \text{ ft-lb}_f/\text{Btu}) \quad (36)$$

where η_{fc} is the adiabatic efficiency of the compressor and ΔT_{fc} is the isentropic total temperature change in °R and can be related to compressor pressure ratio by

$$\Delta T_{fc} = T_{ci} (r_{fc}^{(\gamma-1)/\gamma} - 1) \quad (37)$$

where T_{ci} is the total temperature of the Freon at compressor inlet in °R and r_{fc} is the compressor pressure ratio.

The speed, N_{fc} in rpm, is

$$N_{fc} = (N_s H_{fc}^{3/4}) / \dot{V}_{fc}^{1/2} \quad (38)$$

where \dot{V}_{fc} is the compressor outlet flow in ft³/sec.

The tip diameter, D_{fc} in ft, is:

$$D_{fc} = (60 u_{fc}) / \pi N_{fc} \quad (39)$$

The Freon compressor weight, M_{fc} in lb, is estimated to be (Reference 11)

$$M_{fc} = 50 D_{fc}^3 \quad (40)$$

The motor, to drive the compressor, is estimated to have a weight, M_m in lb, as

$$M_m = H_{p_{fc}} + 18 D_{fc}^2 \quad (41)$$

where the motor horsepower $H_{p_{fc}}$ is

$$H_{p_{fc}} = (\dot{W}_{fc} c_{pg} \Delta T_{fc}) / (\eta_{fc} 42.4 \text{ Btu/min-hp}) \quad (42)$$

and c_{pg} is the specific heat of Freon gas at constant pressure in Btu/lb-F and \dot{W}_{fc} is the Freon flow rate in lb/min.

c. Air Compressor

A compressor is driven either by bleed air (turbine), auxiliary power unit, engine drive (gear), or electric motor. The compressor can be used to provide a pressure source for the environmental control system if engine bleed air is not used or it can be used to balance the cooling turbine for a bootstrap air cycle application. Both radial and axial flow compressors are considered.

The theoretical compressor exit total temperature, T'_{to} , can be obtained from

$$T'_{co} = T_{ci} (P_{co}/P_{ci})^{(\gamma-1)/\gamma} \quad (43)$$

where T_{ci} is the compressor inlet total temperature in °R, P_{ci} is the compressor inlet total pressure in psia, and P_{co} is the compressor outlet total pressure in psia.

The compressor adiabatic efficiency is defined as

$$\eta_c = (T'_{co} - T_{ci}) / (T_{co} - T_{ci}) \quad (44)$$

For a turbine/compressor combination, the work produced by the turbine is absorbed by the compressor. Therefore

$$Z_m \dot{W}_t c_p (T_{ti} - T_{to}) = \dot{W}_c c_p (T_{co} - T_{ci}) \quad (45)$$

where Z_m is the power balance factor due to frictional and other mechanical losses of the entire device, \dot{W}_t is the air flow through the turbine, and \dot{W}_c is the air flow through the compressor.

The weight of the bootstrap compressor is combined with the weight of the turbine as given in Subsection III-5a.

For axial flow compressors, the optimum efficiency is at a specific speed of 1300. The tip Mach number is set to 0.866. The speed (N_a), tip diameter (D_a) and weight M_m are determined using the same equations as described in Subsection III-5b (Reference 12).

d. Fan (Reference 13)

For this project, a single stage axial flow type fan is used. If it is assumed that the fluid is incompressible, provided that the Mach number is less than 0.3, the fan head, H_f in ft-lb_f/lb_m, can be written as:

$$H_f = 144 \Delta P_f / \rho_f \quad (46)$$

where ΔP_f is the pressure increase across the fan in psi, and ρ_f is the air density in lb_m/ft³. The optimum efficiency of the fan is designed to occur at a specific speed, N_s , of 1000. The fan speed is limited to a maximum value of 45,600 rpm. The fan speed, N_f , is calculated to be

$$N_f = N_s H_f^{3/4} / \dot{V}_f^{1/2} \quad (47)$$

where \dot{V}_f is the fan flow in ft³/sec.

The tip diameter in inches is

$$D_f = 12.65 (60 \dot{V}_f / (\pi N_f))^{1/3} \quad (48)$$

The weight of the fan, M_f in lb, is estimated by the expression (Reference 13)

$$M_f = 60 D_f^3 + 0.5 \quad (49)$$

The motor weight is estimated by the expression

$$M_{mf} = H p_f + 18 D_f^2 \quad (50)$$

where the horsepower, Hp_f is

$$Hp_f = H_f \dot{W}_f / (33,000 \eta_f) \quad (51)$$

and \dot{W}_f is the fan flow in lb/min and η_f is the efficiency of the fan.

e. Heat Exchanger

For this project, heat exchanger analyses are applied to an air/air heat exchanger, air/liquid heat exchanger, condenser, and evaporator. In the performance analysis, pressure, temperature, flow, volume, and weight are determined. The heat exchanger effectiveness, η_{hx} , is assumed to be a function of the fluid flows through the core and is given by

$$\eta_{hx} = (T_{1i} - T_{1o}) / (T_{1i} - T_{2i}) \quad (52)$$

and T_{1i} is the temperature of the hot fluid entering the heat exchanger in °R, T_{1o} is the temperature of the hot fluid leaving the heat exchanger in °R, and T_{2i} is the temperature of the heat sink fluid entering the heat exchanger in °R, and $(\dot{W} c_p)_1 < (\dot{W} c_p)_2$

For the evaporator design point the Freon temperature is set at 24°F below exit air temperature. The evaporating temperature is the saturation temperature of the refrigerant at the pressure in the evaporator. The condensing temperature of the refrigerant at the design point is set at 10°F higher than the temperature of the heat sink fluid leaving the condenser. The condensing temperature is assumed as the saturation temperature of the refrigerant at the pressure in the condenser.

The fixed weight of the heat exchanger is a function of the core weight and manifold weight that encloses the core. The weight of manifold depends on the pressure level of the fluids considered, on the pressure drop available, on the installation requirements, and, in general, on the particular application. The weight of the manifold can be a large portion for small heat exchangers. In this analysis, the

total exchanger weight is related to the core weight and volume by an empirical factor based on the present state-of-the-art.

The core weight, in lb, is (Reference 14)

$$M_{hc} = 1.1 C_i V_{hx} \quad (53)$$

where C_i is 31.1 lb/ft^3 for aluminum core and 69.8 lb/ft^3 for a stainless steel core and V_{hx} is the volume of the entire heat exchanger in ft^3 .

The heat exchanger weight is given in lb as

$$M_{hx} = M_{hc} (12 / V_{hx})^{.118} \quad (54)$$

(1). Air/Air Heat Exchanger

The performance analysis used for the air/air heat exchanger described in Subsection II-3a(2), is presented in Appendix B and sample calculations related to Heat Exchanger Number 1 in Cycle A-2 is presented in Appendix A. This is an approximate method for analyzing flight heat exchangers and is so made in an effort to reduce the complexity of design procedures. The heat exchanger has compact cross flow cores with either plate/fin or tube/fin geometry. The effectiveness curves assumed for the bleed air/ram air heat exchanger and for the bleed air/recirculation air heat exchanger is shown in Figure A-1.

(2). Air/Liquid Heat Exchanger

The performance analysis used for the air/liquid heat exchanger described in Subsection II-3a(2), is derived from Kays and London's, "Compact Heat Exchangers" (Reference 15). The heat exchanger has a compact crossflow core with finned flat tube geometry (11.32 fins per in.) and liquid flowing in the tube.

(3). Evaporators and Condensers

The procedure for sizing evaporators and condensers is applicable to a plate-fin geometry. Tube-plate heat exchangers have certain advantages and disadvantages. Uniform distribution of refrigerant to several tubes is more readily accomplished than is distribution along the span of several plates. The tubes can be folded back in a multipass arrangement to achieve slightly better effectiveness. However, plate-fin designs usually are more compact and typically have lower refrigerant side pressure drop. Plate-fin geometry selected for evaporators and condensers are triangular louvered plate-fin surfaces, 3/8 inch louver spacing, 6.06 fins per inch for the air side and rectangular offset plate-fin surface, and 15.75 fins per inch for the refrigerant side.

(4). Evaporator Sizing

Two types of performance analyses are used, one for the air/Freon evaporator and the other for the liquid/Freon evaporator. For the air/Freon evaporator, the heat exchanger performance is quoted from Reference 15. The assumptions are made that the heat transfer coefficient on the Freon side is $200 \text{ Btu/hr ft}^2 \text{ }^\circ\text{F}$ (Reference 16) and the Freon evaporative temperature is constant. For the liquid/Freon evaporator the heat exchanger performance is quoted from Reference 16 by AiResearch Manufacturing Company for aircraft applications, with the following simplifications employed.

- (1) Heat transfer coefficient on both the Freon and liquid side is $200 \text{ Btu/hr ft}^2 \text{ }^\circ\text{F}$.
- (2) Ratio of fanning friction factor to Colburn j-factor, f/j , is 3.5.
- (3) Overall fin effectiveness equals to 0.85.
- (4) Heat transfer surface area/heat exchanger volume is $30 \text{ in}^2/\text{in}^3$.

(5). Condenser Sizing

Three types of performance analyses are used: one for the air/Freon condenser, one for the liquid/Freon condenser, and the other for a combination air-liquid/Freon condenser. For the air/Freon condenser, the heat exchanger performance is quoted from Reference 15 with the assumptions that the heat transfer coefficient of the Freon side is 200 Btu/hr ft² °F (Reference 16) and the Freon condenser temperature is constant. For the liquid/Freon condenser, the heat exchanger performance is quoted from Reference 16.

The procedure for sizing the air-liquid/Freon condenser is divided into two parts: air/Freon heat exchanger and liquid/Freon condenser. For this analysis, the assumption is made that the Freon is in the superheated state for the air/Freon section. Therefore, the heat exchanger performance can be estimated from Reference 15. The technique used in Appendix B cannot be used here since assumptions were based on an air/air heat exchanger. For the liquid/Freon condenser, the performance is determined by the analysis given in Reference 16. The assumptions are as follows:

- (a) The heat transfer coefficient for the liquid side (boiling water in this case) is 300 Btu/hr ft² °F.
- (b) The heat transfer coefficient for the Freon side (boiling Freon in this case) is 200 Btu/hr ft² °F.
- (c) A condensing temperature of 10°F above the boiling water is selected.

f. Liquid Cooled Compartment Wall

The weight of the liquid cooled wall, in lb, consisting of a tube/fin aluminum plate, thermal insulation, and liquid is

$$M_{wl} = (\rho x)_{in} A_c + (\rho x)_{al} A_c + \frac{(\rho \pi d^2 L')}{4} A_c \quad (55)$$

Where ρ is the density in lb/ft³, x is the thickness in ft, A_c is the compartment wall area in ft², d is the tube diameter in ft, L' is the

length in ft/ft², _{in} is the subscript for thermal insulation, _{al} is the subscript for the aluminum plate thickness, and _l is the subscript for the fluid in the liquid cooling wall tubes.

The aerodynamically induced heat load through the thermal insulation, Q_{in} in Btu/hr, is

$$Q_{in} = k_{in} A_c \Delta T_{in} / x_{in} \quad (56)$$

where k_{in} is the thermal conductivity of the insulation material in Btu/ft-F-hr and ΔT_{in} is the average temperature difference between aluminum plate and fuselage skin in °F.

The liquid flow, \dot{W}_{wl} in lb/min, is

$$\dot{W}_{wl} = Q_{in} / (c_p \Delta T_{lf}) \quad (57)$$

where ΔT_{lf} is the temperature difference between the liquid going into the compartment wall passages and liquid exhausting out of the wall.

g. Air Cooled Compartment Wall

The weight of the air cooled compartment wall consisting of a compartment wall and thermal insulation between the air gap and fuselage is

$$M_{aw} = (\rho x)_{in} A_c + (\rho x)_{aw} A_c \quad (58)$$

where subscript _{aw} stands for compartment air wall.

The air flow, \dot{W}_{wa} in lb/min, is

$$\dot{W}_{wa} = Q_{in} / (c_p \Delta T_{af}) \quad (59)$$

where ΔT_{af} is the temperature difference between the air entering the air gap in the compartment wall and air leaving the air gap in the wall and \dot{W}_{wa} is the air flow through the cooling wall in lb/min.

h. Engine Weight

A proportional amount of fixed engine weight is charged to the environmental control system since bleed air and power is obtained from the engine. Two engine weight terms will be used, specific engine weight (SEWHP) in lb/hp and specific engine weight per thrust (SEWT).

The engine weight penalty, in lb, for the total horsepower generated for the environmental control system is

$$M_{eh} = (\text{SEWHP}) \sum_{i=1}^n \text{hp}_i \quad (60)$$

where i is the index of each engine-driven component.

The engine weight penalty, in lb, for the loss of engine thrust is

$$M_{th} = (\text{SEWT}) \sum_{i=1}^n \text{Th}_r \quad (61)$$

where Th_r is the drag loss in lb, as given in Equation 7, i is the index of each item involving drag.

SECTION IV

RESULTS AND CONCLUSIONS OF PERFORMANCE
AND WEIGHT PENALTIES ANALYSES

1. INTRODUCTION

In this section, the results and conclusions of the performance and the weight penalties analyses are presented. In order to make reasonable comparisons between systems, certain assumptions were drawn that were common for all systems and are presented in Subsection IV-2. Using the component analysis described in Section III, the results of the performance analysis for each complete environmental control system were obtained and are presented in Subsections IV-3 and -4. The performance was calculated for Mach 3, Mach 1, and ground conditions. The results are shown later in Figures 31 through 45. A sample calculation to show how these results were obtained is given in Appendix A.

Using the Stepwise Integration Method derived in Section III, the weight penalties are evaluated and summarized in Subsections IV-5 and -6 for each environmental control system except for Cycle V-3. The penalties for each environmental control system are shown later in tables. These penalties are based on the mission profile in Figure 11. Fixed weight penalties were determined for all components shown in Figures 5 through 8 except for the odor and contaminate remover, fuel/liquid heat exchanger, and air and liquid lines.

2. ASSUMPTIONS

The following assumptions were drawn for all cooling systems.

- a. The aircraft configuration was the same except for differences in the cooling wall (Figure 4).
- b. The flight profile was the same (Figure 11).
- c. The aircraft fuselage temperature was 500°F at Mach 3 speed (Reference 17).
- d. The air circulation per passenger was 20 cfm and the average heat generated per passenger was 475 Btu/hr. The number of passengers and crew was 256 people.

e. The internal heat load and aerodynamically induced heat load were each a set value for all cooling systems. The solar radiator was not considered.

f. The total environmental control system was divided into three identical systems. Two of the systems supplied air to the passenger compartment and the third system split the cooling air between the passenger compartment and pilot compartment as shown in Figure 4. For each semiclosed environmental control system fifty percent of the exhaust air was recirculated through the compartment for Mach 3 and Mach 1 conditions.

g. A comfortable compartment condition was maintained between an air temperature range of 66°F and 77°F and inlet air temperature between 48°F and 55°F for all flight conditions.

h. The following design point efficiencies, η , were selected based on Reference 18.

Cooling Turbine	Bootstrap Compressor	Engine and Recirculating Compressor	Fan	Pump
0.8	0.65	0.8	0.7	0.92

i. The following design point thermal effectiveness, η_{hx} , were selected between the following ranges.

Liquid/Air Heat Exchanger	Air/Air Heat Exchanger	Recirculate Air/Air Heat Exchanger
0.95 - 0.90	0.85	0.725 - 0.56

3. PERFORMANCE OF THE OPEN AND SEMICLOSED BOOTSTRAP AIR CYCLE ENVIRONMENTAL CONTROL SYSTEMS

The performance of the open and semiclosed bootstrap air cycle environmental control systems for each flight condition are shown in

Figures 31 through 36 and sample calculations of the semiclosed bootstrap environmental control system is presented in Appendix A.

For the Mach 3 condition, the environmental control system operated under maximum cooling loads, 417,000 Btu/hr, due to passenger, aerodynamic, and electronic heating loads. The bleed air, required to turn the turbine/bootstrap compressor, started at a moderately high temperature out of the engine compressor. Even though the ram air temperature was 1098°R, the air was an adequate heat sink to cool the bleed air through Heat Exchanger Number 1. Fuel/Air Heat exchangers were used to cool the bleed air also and the temperature of the bleed air was reduced as low as possible through the Heat Exchanger Number 4 ($\eta = 0.95$) so the maximum cooling was obtained. The cooling turbine exhaust air was mixed with by-pass air in order to obtain the desired inlet compartment air temperature of 507°F.

For Mach 1 condition, the environmental control system operated under a minimum cooling load, 158,000 Btu/hr, due only to passenger and electronic equipment heat loads. This results in a decrease in the amount of bleed air through the cooling turbine and by-passing air as shown in Figures 32 and 35. The ram air was an adequate heat sink to cool the bleed air, without requiring cooling through Heat Exchangers Numbers 2 and 3. The liquid heat sink was used to cool the bleed air out of the compressor through Heat Exchanger Number 4. Ram air cooling could have been used, however, this would have required an extra heat exchanger.

For the ground condition, the cooling load was also 158,000 Btu/hr. The relative humidity of the ambient air was assumed to be 100 grains water/lb dry air. The moist air expanded through the cooling turbine and some of water vapor in the moist air condensed and thereby released latent heat. Because of this effect, the turbine outlet air temperature was increased from 442°R (dry bulb) to 486°R for the semiclosed system. Even though the cooling load was lower than Mach 3 condition, the air flow required through the cooling turbine was approximately the same as

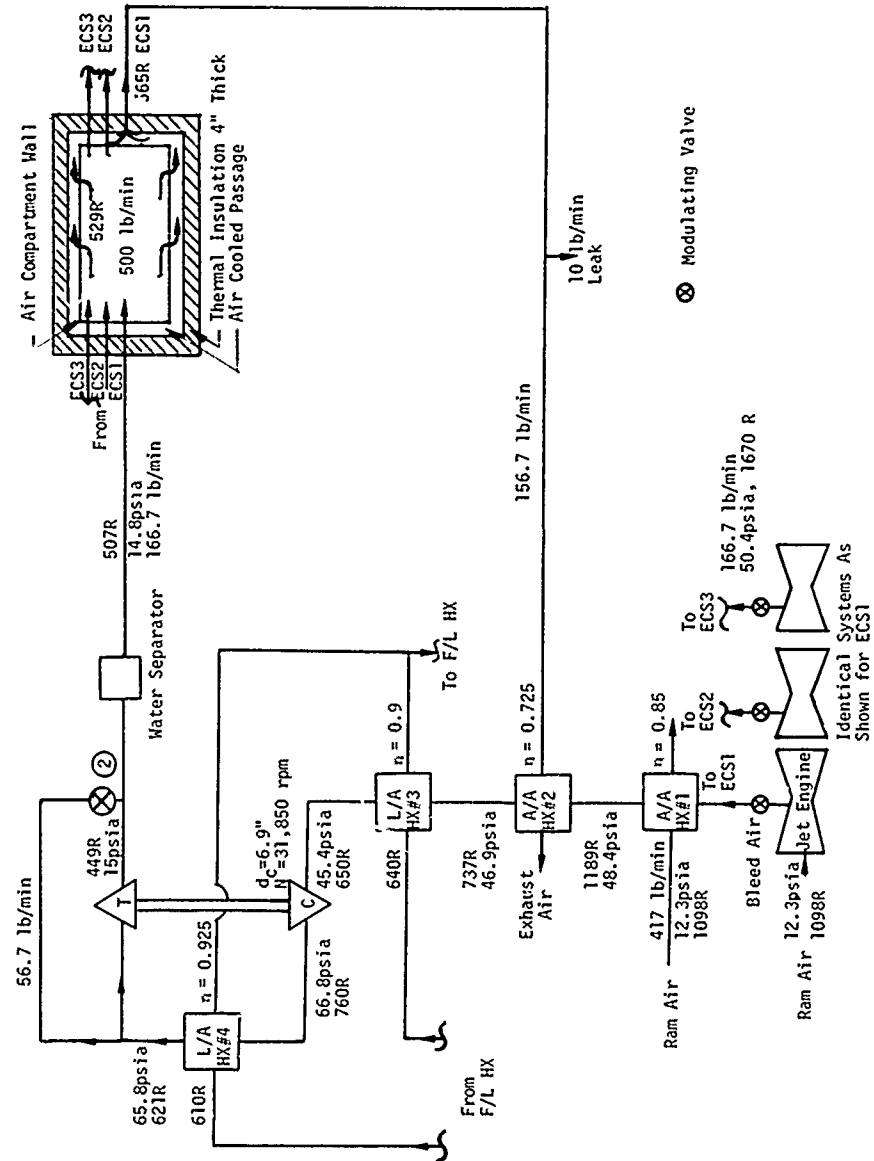


Figure 31. Performance Schematic, Bootstrap Air Cycle Environmental Control System with Air Cooled Wall, Operation at Mach 3 Condition

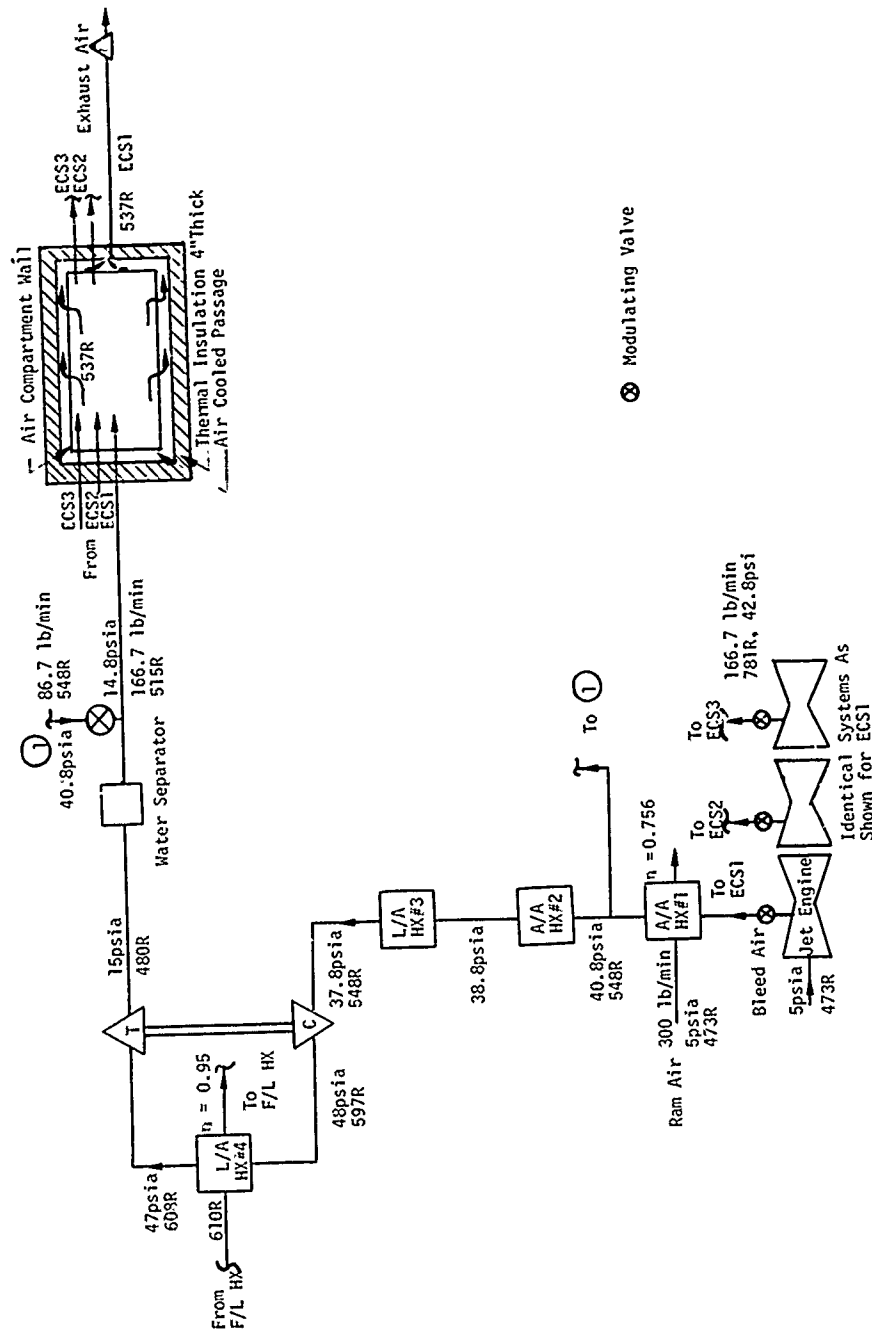


Figure 32. Performance Schematic, Bootstrap Air Cycle Environmental Control System with Air Cooled Wall, Operation at Mach 1 Condition

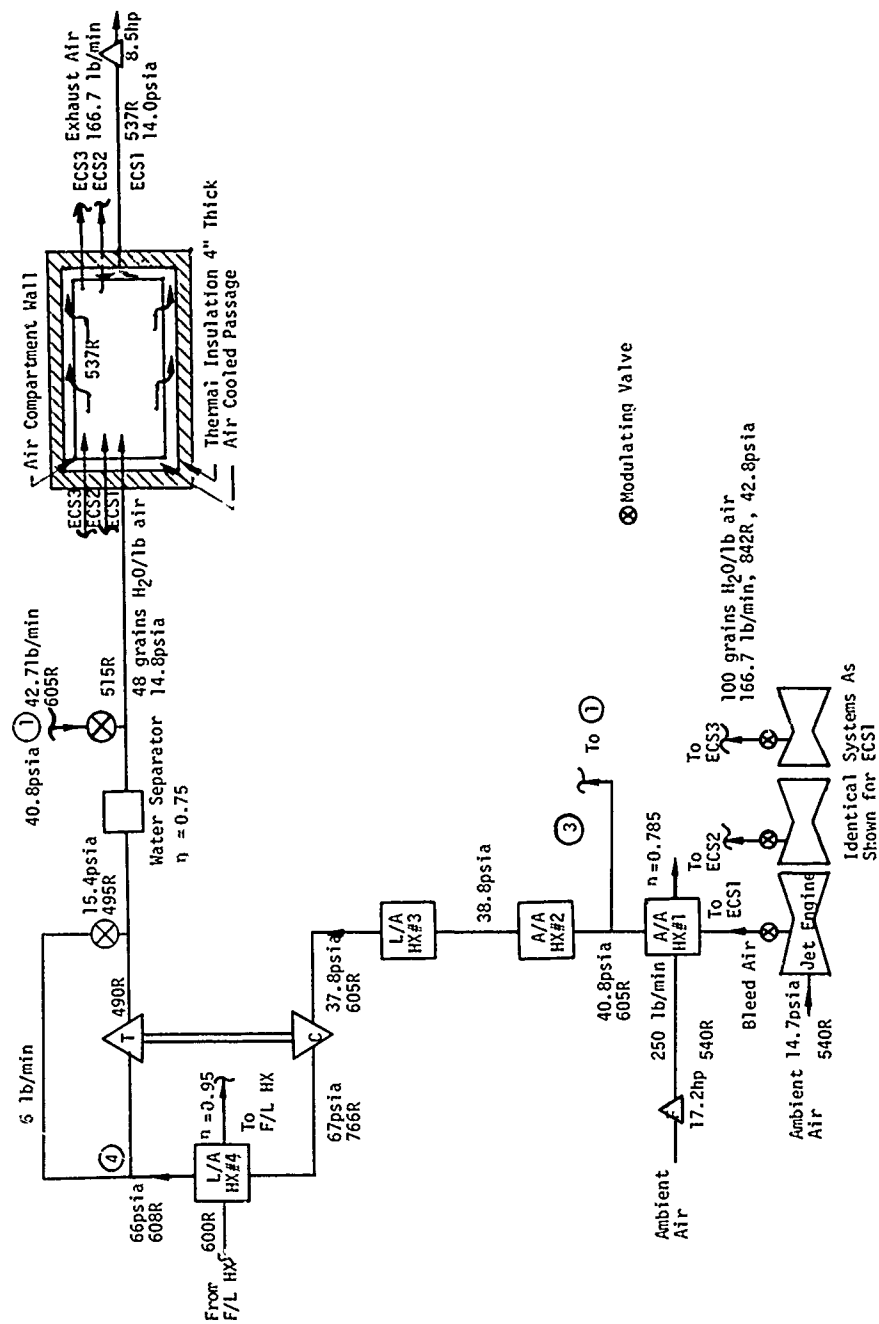


Figure 33. Performance Schematic, Bootstrap Air Cycle Environmental Control System with Air Cooled Wall, Operation at Ground Condition

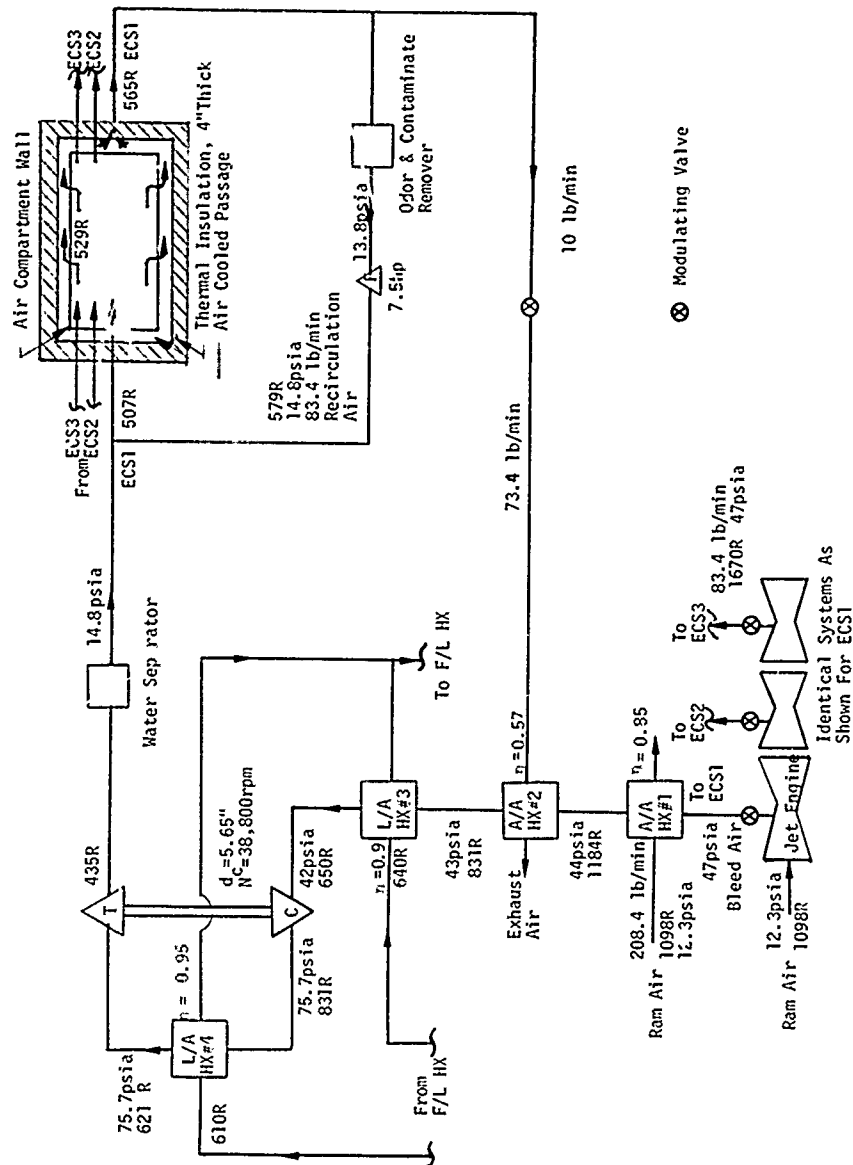


Figure 34. Performance Schematic, Semiclosed Bootstrap Air Cycle Environmental Control System with Air Cooled Wall, Operation at Mach 3 Condition

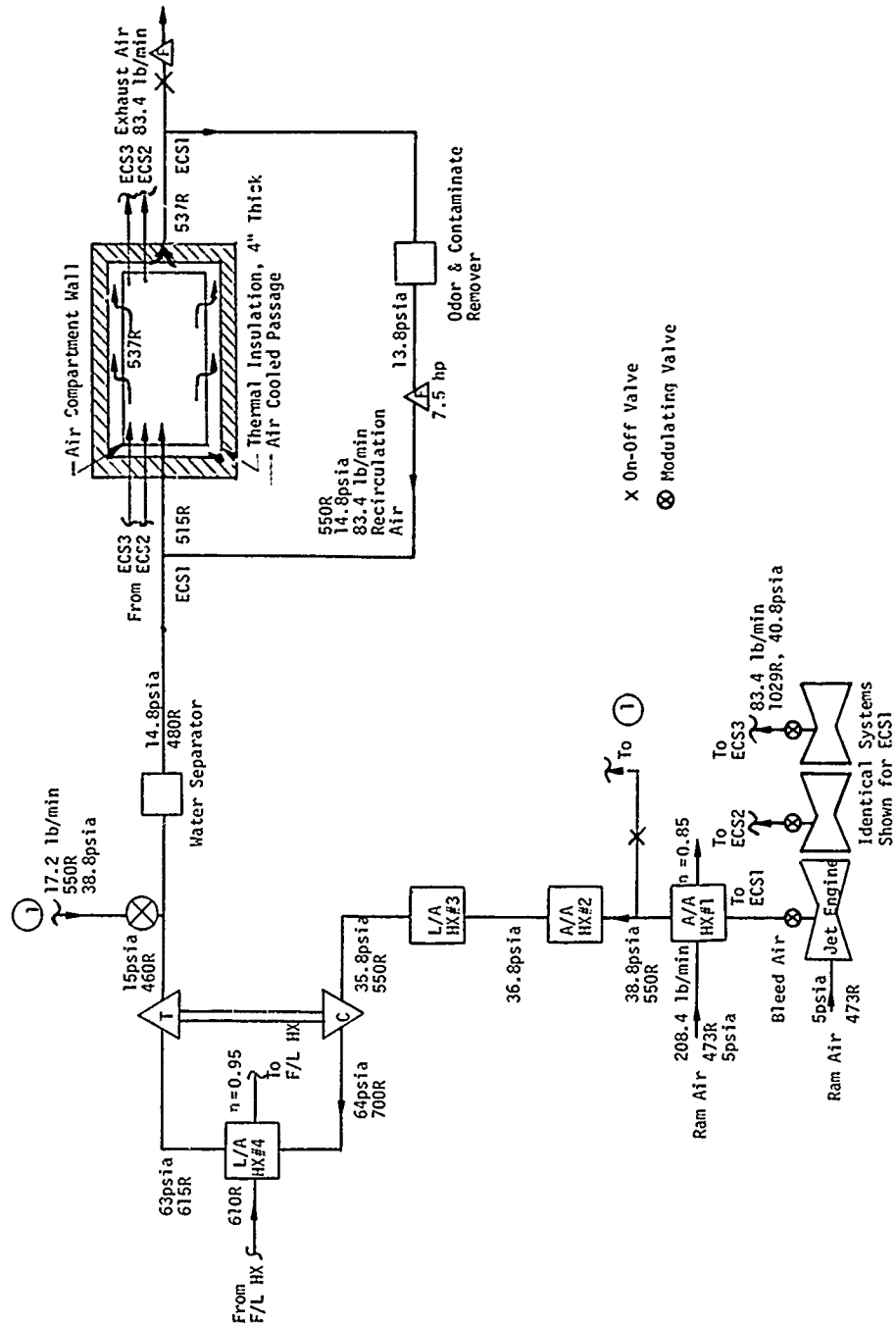


Figure 35. Performance Schematic, Semiclosed Bootstrap Air Cycle Environmental Control System with Air Cooled Wall, Operation at Mach 1 Condition

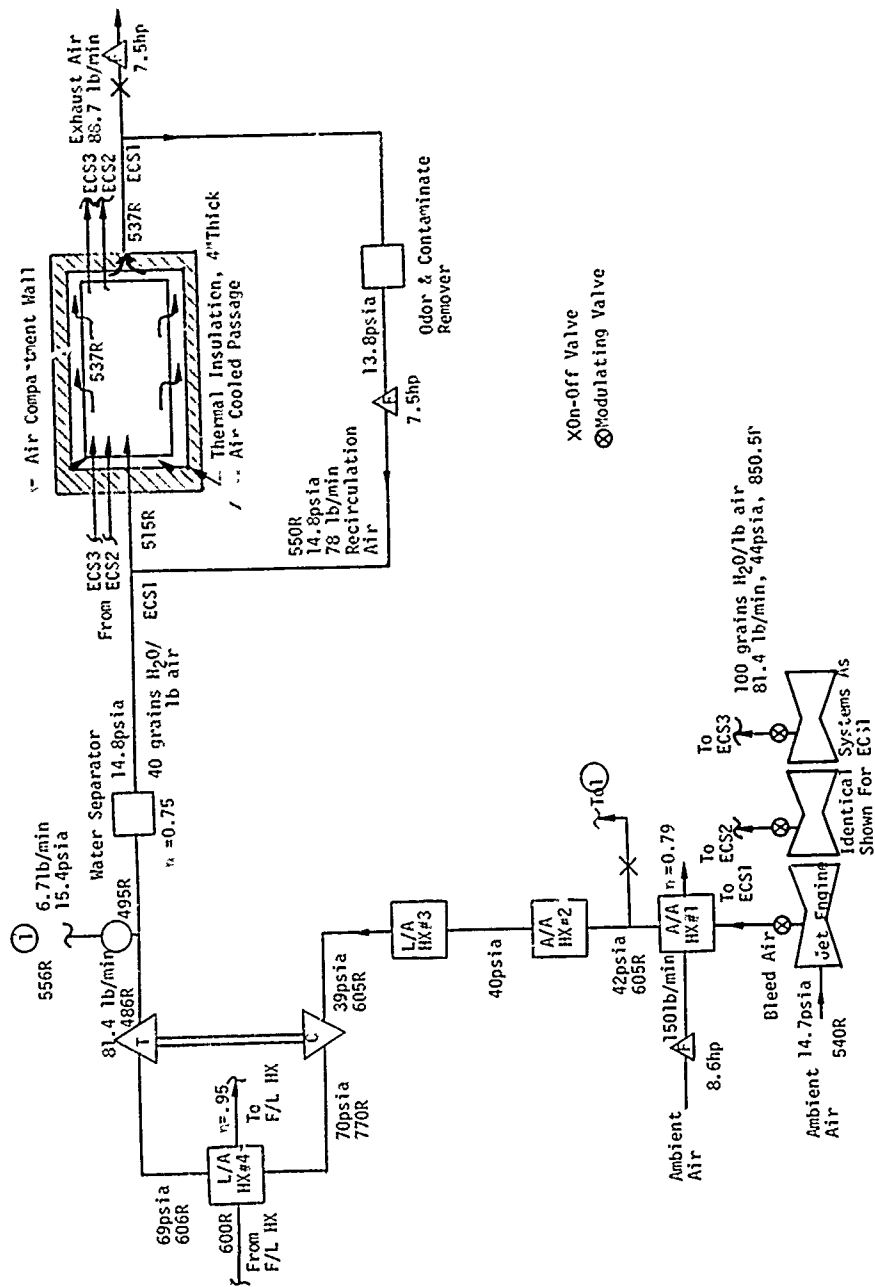


Figure 36. Performance Schematic, Semiclosed Bootstrap Air Cycle Environmental Control System with Air Cooled Wall, Operation at Ground Condition

Mach 3 condition since latent heat was added to the air. The ground air flow through Heat Exchanger Number 1 was regulated so that the bleed air temperature out of Heat Exchanger Number 1 was 605°R for both systems.

4. PERFORMANCE OF VAPOR CYCLE ENVIRONMENTAL CONTROL SYSTEMS

The performance of the vapor cycle environmental control systems for each flight condition are shown for

1. Semiclosed Vapor Cycle Environmental Control System with an air cooled compartment wall (Cycle V-1, Figures 37 through 39).
2. Semiclosed Vapor Cycle Environmental Control System with a liquid cooled compartment wall (Cycle V-2, Figures 40 through 42).
3. Semiclosed Vapor Cycle Environmental Control System with a liquid cooled compartment wall and without a water boiler (Cycle V-3, Figures 43 through 45).

All of the vapor cycle environmental control systems were designed to have the characteristics as shown in Figure 46 for the pressure-enthalpy diagram. The Freon temperature in both the liquid and air evaporator was set at 28°F so that any condensed water on the air side would not freeze. The Freon temperature in the flight and ground condenser was set equal to 180°F for all systems. The temperature of the water out of the condenser was 165°F. For the operation of the ground condenser, the ram air flow was adjusted so that the air temperature out of the condenser was 210°F for Cycle V-1 and V-2 and for Cycle V-3, the liquid temperature out of the condenser was 165°F.

For Mach 3 condition, the environmental control system operated under maximum cooling load, 417,000 Btu/hr, for Cycles V-1 and V-2 and 577,000 Btu/hr for Cycle V-3. The cooling load was higher for Cycle V-3 since the compartment insulation was 2 inches thick instead of 4 inches.

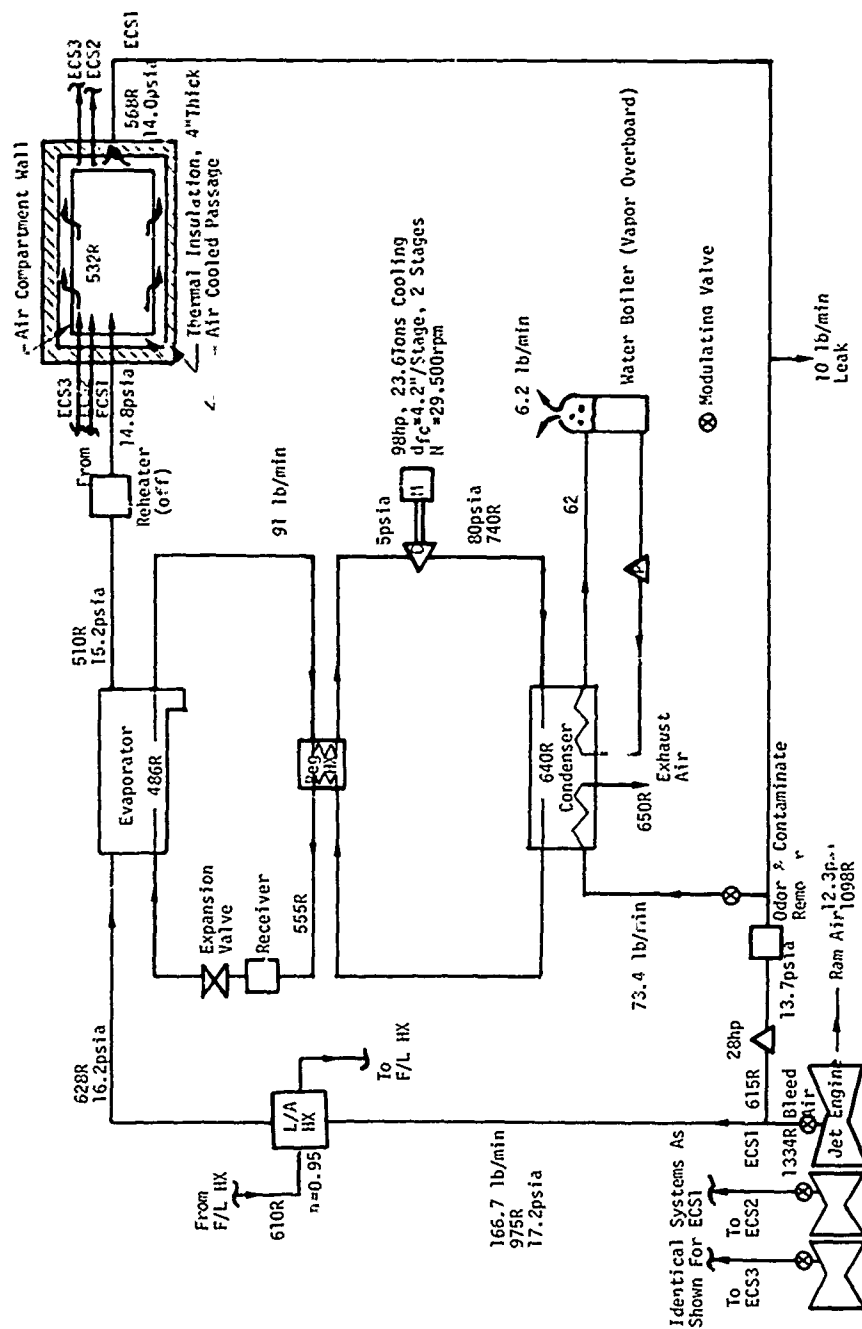


Figure 37. Performance Schematic, Semiclosed Vapor Cycle Environmental Control System with Air Cooled Wall, Operation at Mach 3 Condition

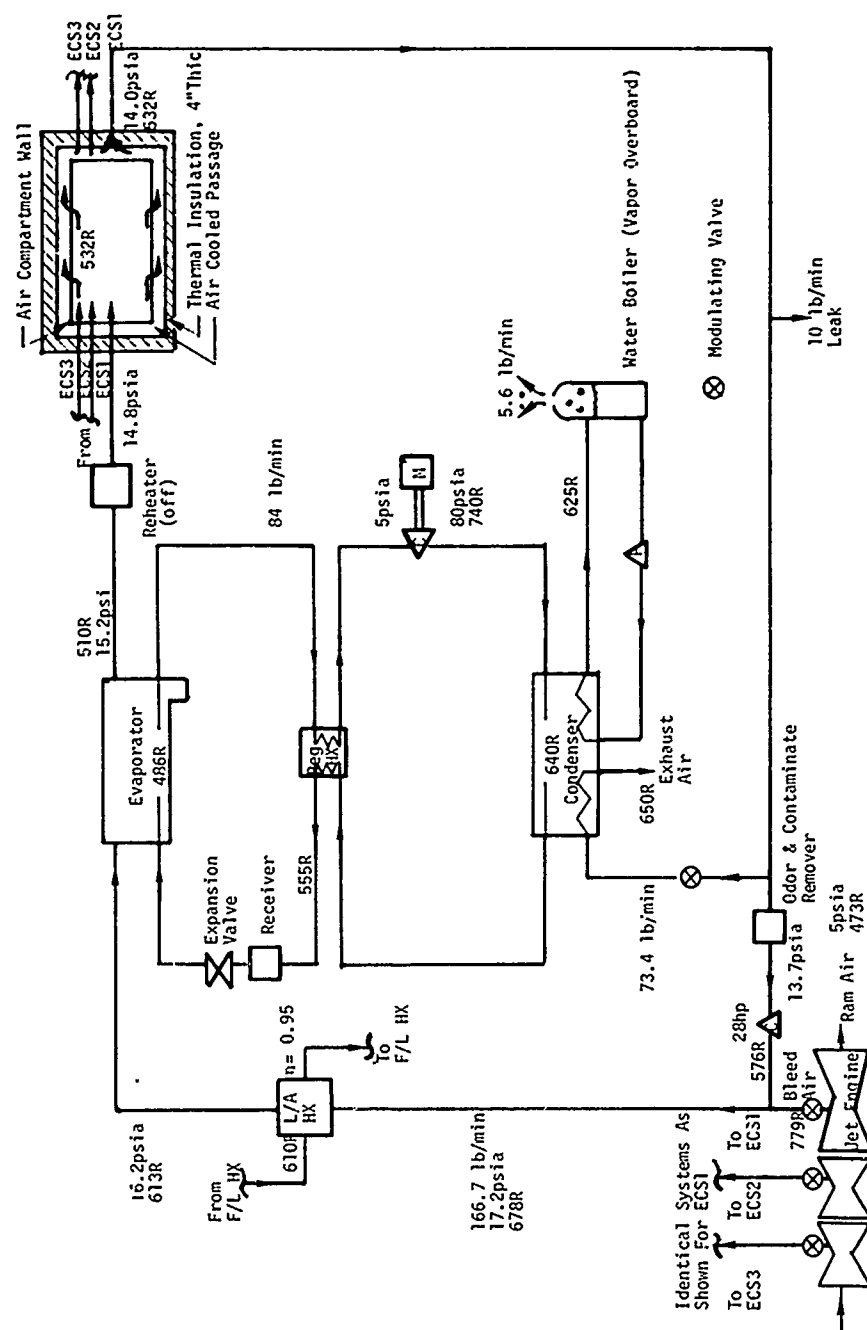


Figure 38. Performance Schematic, Semiclosed Vapor Cycle Environmental Control System with Air Cooled Wall, Operation at Mach 1 Condition

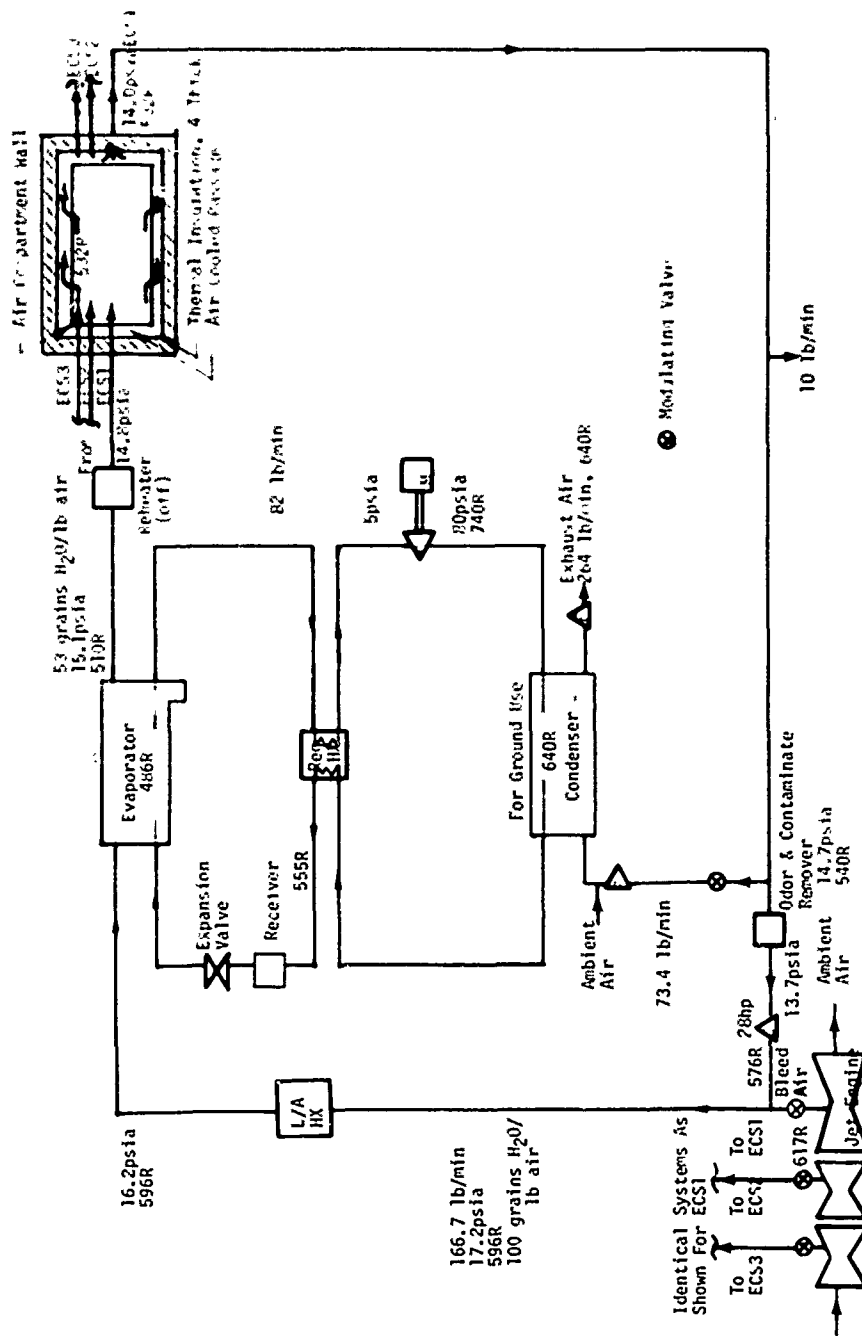


Figure 39. Performance Schematic, Semiclosed Vapor Cycle Environmental Control System With Air Cooled Wall, Operation at Ground Condition

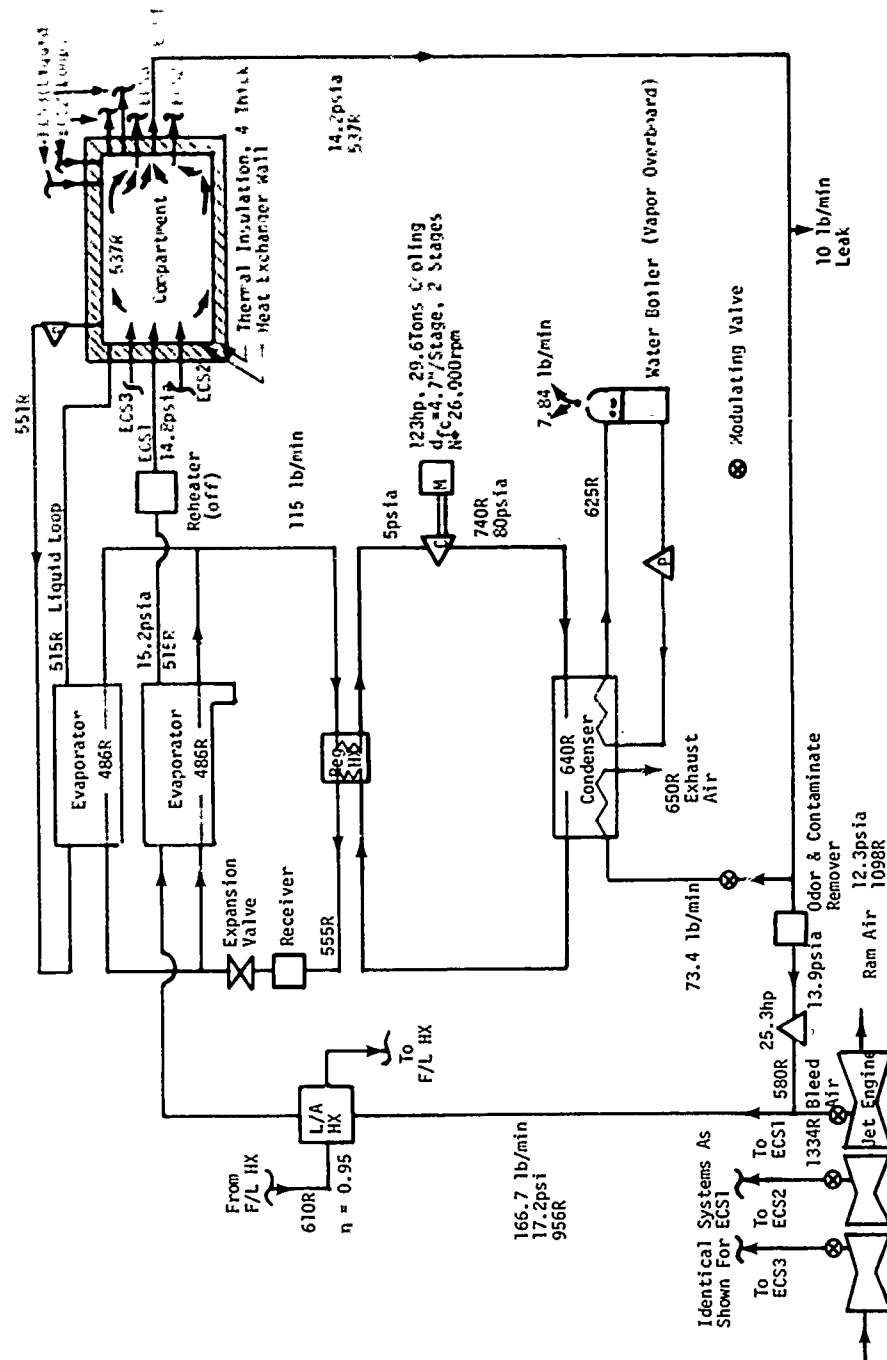


Figure 40. Performance Schematic, Semiclosed Vapor Cycle Environmental Control System with Liquid Cooled Wall, Operation at Mach 3 Condition

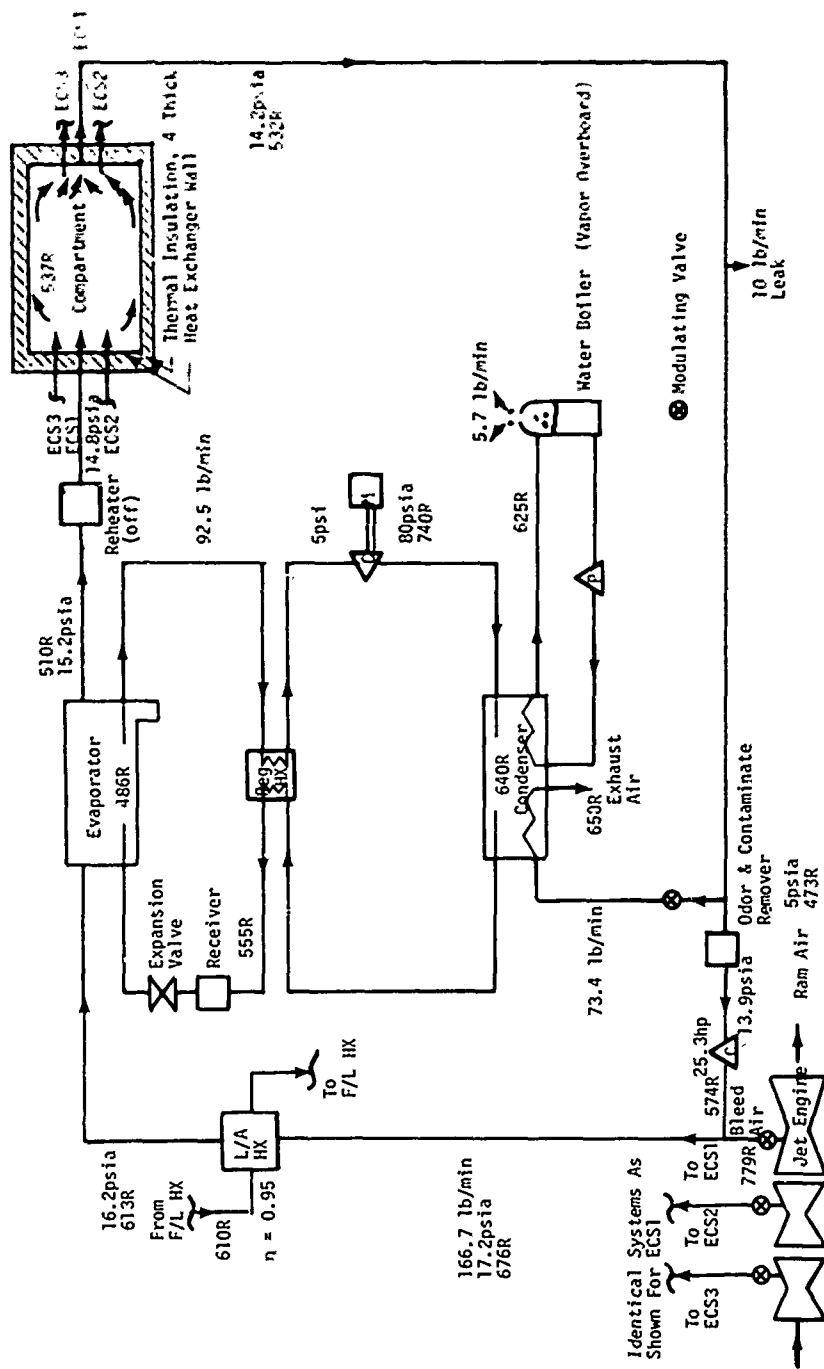


Figure 41. Performance Schematic, Semiclosed Vapor Cycle Environmental Control System with Liquid Cooled Wall, Operation at Mach 1 Condition

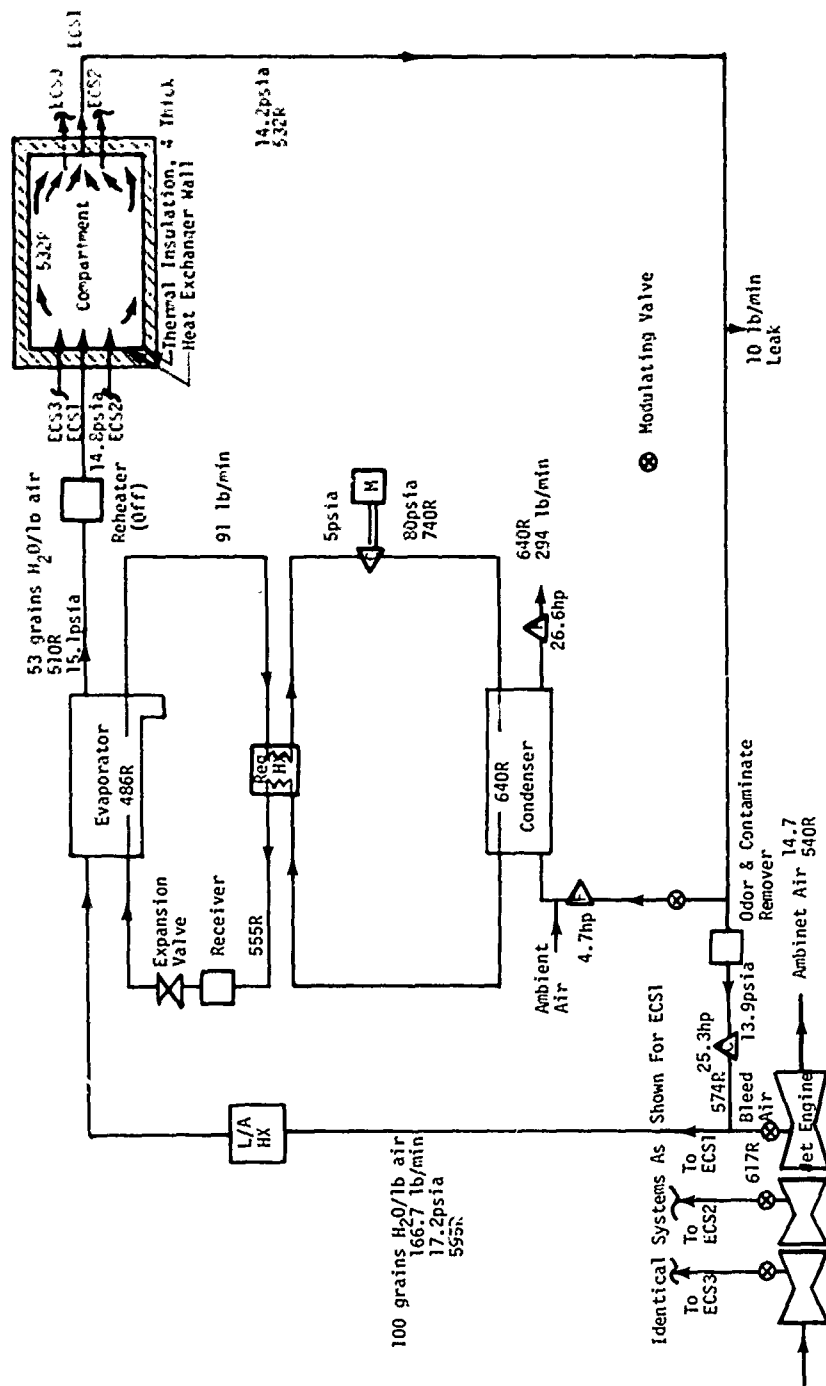


Figure 42. Performance Schematic, Semiclosed Vapor Cycle Environmental Control System with Liquid Cooled Wall, Operation at Ground Condition

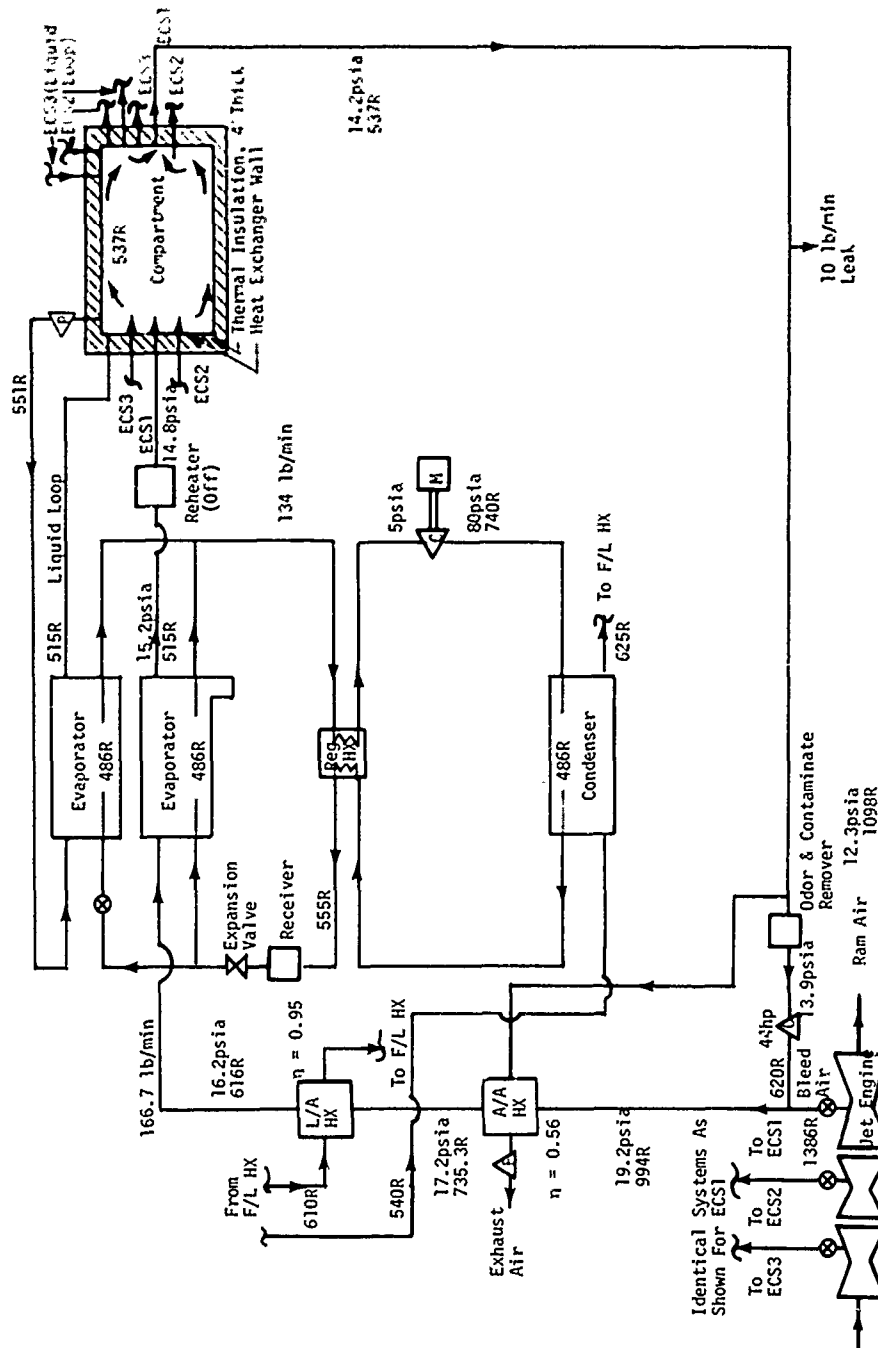


Figure 43. Performance Schematic, Semiclosed Vapor Cycle, Environmental Control with Liquid Cooled Wall/ Without Water Boiler, Operation at Mach 3 Condition

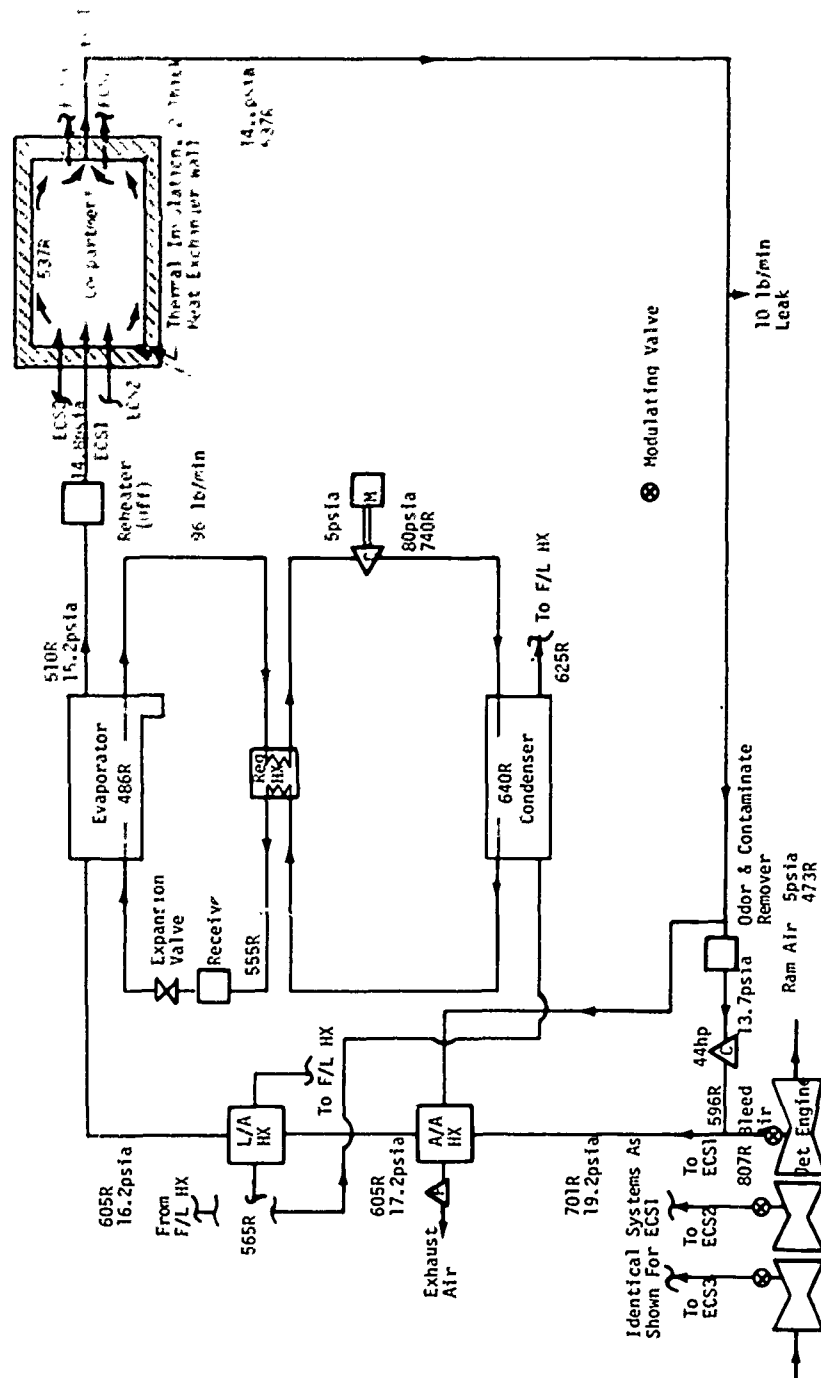


Figure 44. Performance Schematic, Semiclosed Vapor Cycle Environmental Control System with Liquid Cooled Wall/Without Water Boiler, Operation at Mach 1 Condition

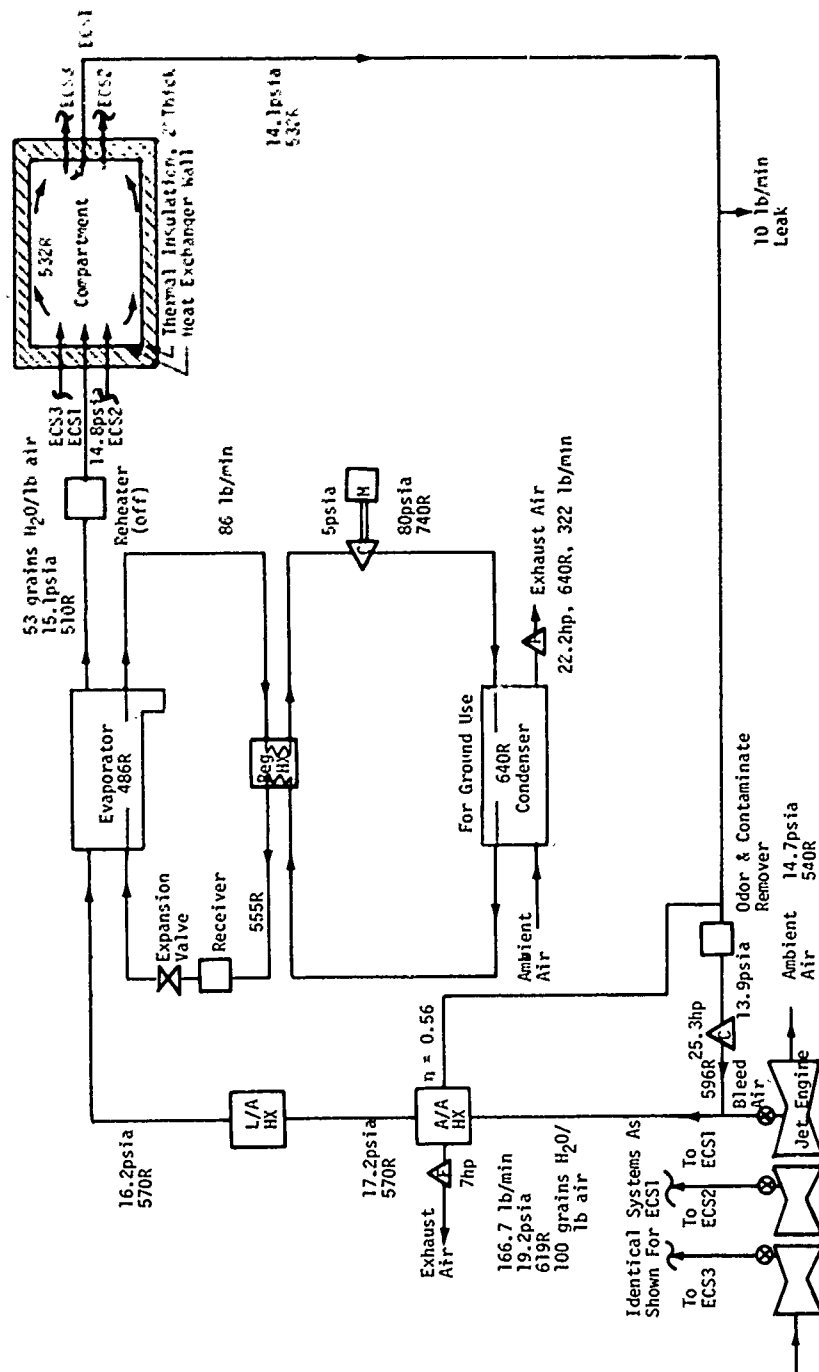


Figure 45. Performance Schematic, Semiclosed Vapor Cycle Environmental Control System with Liquid Cooled Wall/Without Water Boiler, Operation at Ground Condition

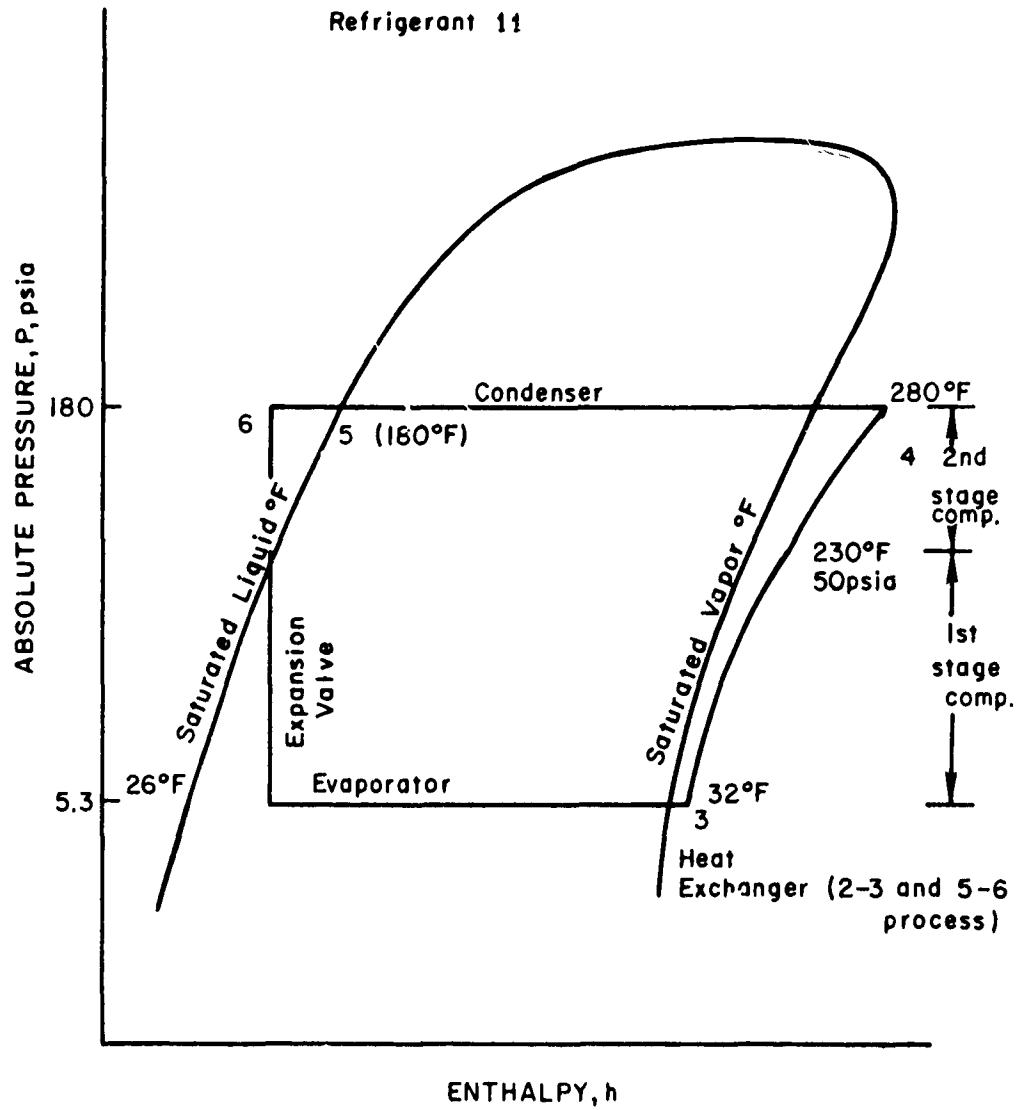


Figure 46. P-H Diagram Of The Vapor Refrigeration Cycle Used for VC1 Through VC3

The liquid cooling load for the liquid/air heat exchanger, evaporator, and condenser varied for each vapor cycle environmental control system. For Cycle V-1, the total evaporator and condenser cooling loads were the smallest of the three systems for Mach 3 condition. The liquid cooling load for the liquid/air heat exchanger was the largest of the three systems. For Cycle V-2, the total evaporator and condenser cooling loads were lower than Cycle V-3 and the liquid cooling load for the liquid/air heat exchanger was higher than Cycle V-3. Even though the cooling load was maximum for the Cycle V-3, water was not used since precooled fuel was used as the heat sink.

For Mach 1 and ground conditions, each system operated having a total cooling of 158,000 Btu/hr. The evaporator and condenser cooling loads were approximately the same for all environmental control systems. The bleed air was cooled by the liquid in the liquid/air heat exchanger for Cycles V-1 and V-2 and by the recirculated air in the air/air heat exchanger for Cycle V-3. For the ground condition, the moist air condensed in the evaporator, releasing 100,600 Btu/hr in latent heat.

The major components of the vapor cycle environmental control system were sized for Mach 3 condition. The Freon flow was determined for the Cycle V-1 based on the bleed air cooled through the air/Freon evaporator. The Freon flow was determined for the Cycles V-2 and V-3 based on the bleed air cooled through the air/Freon evaporator and liquid cooled through the liquid/Freon evaporator. The two stage compressor was sized based on the Freon flow at Mach 3 condition.

5. WEIGHT PENALTY OF THE SEMICLOSED AND OPEN BOOTSTRAP AIR CYCLE ENVIRONMENTAL CONTROL SYSTEMS

The semiclosed bootstrap air cycle environmental control system had the least fixed weight ($M_{tw} = 2523.1$ lb), and the least total penalty ($Pl_T = 10,606.8$ lb) even though the fuel penalty, Pl_{TS} , accounted for 76.2% of Pl_T . The relatively high percentage of fuel penalty was due to bleed and ram air fuel penalty. Even with the expendable evaporant, water, for the vapor cycle environmental control system excluded, the semiclosed bootstrap environmental control system was still the lightest

fixed weight system. Such heavy items as the compressor, condenser, evaporator, and heat exchanger in the vapor cycle contributed more to the weight in the refrigeration unit than the heat exchangers, turbine/bootstrap compressor, and fan in the air cycle unit. A comparison of the vapor cycle and air cycle environmental control system weights, M_{ecs} from Tables 1 and 2 showed

$$\begin{aligned} M_{ecs} &= 1547.1 \text{ lb for Cycle V-1} \\ &= 756.9 \text{ lb for Cycle A-2} \end{aligned}$$

The total weight and penalty of the air and vapor cycle ECS are shown in Table 3.

When comparing the open and semiclosed bootstrap air cycle environmental control system, weight savings were achieved in every penalty category for the latter system. The fixed weight, M_{dw} , of the semiclosed system (including extra components such as recirculation duct, fan, and odor and contaminate remover subsystem) was only 44% of the open system. Fixed weights of similar components and subsystems were also smaller except for the thermal insulation weight, which was the same.

The bootstrap air cycle environmental control system had the largest total penalty of 18624.6lb. Since this system was open, the total bleed air flow required was 500 lb/min, which resulted in a ram air flow of 1,251 lb/min at Mach 3 condition. Therefore, the bleed and ram air penalty were the largest of all systems.

6. WEIGHT PENALTY OF THE VAPOR CYCLE ENVIRONMENTAL CONTROL SYSTEMS

Cycle V-1 had the smallest total fuel penalty, Pl_f , but the total fixed weight, M_{tw} , was 283% larger than for the semiclosed bootstrap air cycle environmental control system. The total fixed weight, M_{tw} , was high since the fixed weight of the vapor cycle components and expendable water were high. However, the total fuel weight penalty was based on a low bleed and ram air fuel penalty, and low expendable coolant fuel penalty. The total fuel weight was as important as the

TABLE 1
FIXED WEIGHT IN AIR CYCLE ENVIRONMENTAL CONTROL SYSTEMS

Component	Semiclosed Bootstrap Air Cycle		Bootstrap Air Cycle	
	lb	γ, ft^3	lb	γ, ft^3
Heat Exchanger #1	39.7	1.57	94.5	3.92
Heat Exchanger #2	27.3	0.226	155.0	1.61
Heat Exchanger #3	27.4	0.99	42.2	1.57
Turbine/Compressor	10.3		18.7	
Heat Exchanger #4	27.4	0.99	42.2	1.57
Fans	57.6		53.0	
Water Separator	11.0		11.0	
Valves	<u>51.5</u>		<u>56.4</u>	
M_{ecs}	252.3 lb/unit (756.9 lb total)		474.0 lb/unit	
M_{eh} , Engine Hp Wt	77.8		160.5	
M_{th} , Engine Th Wt	<u>49.6</u>		<u>99.4</u>	
M_{ecse}	379.1 lb/unit		733.9	
3 units	1139.1 lb		2201.7 lb	
M_{in} , Insulation	<u>1384.0</u>		<u>1384.0</u>	
M_{tw} , System	2523.1		3585.7	

TABLE 2

FIXED WEIGHT IN VAPOR CYCLE ENVIRONMENTAL CONTROL SYSTEM

	Vapor Cycle With Air Wall		Vapor Cycle With Liquid Wall	
	lb	<u>v, ft³</u>	lb	<u>v, ft³</u>
Compressor	106.2		131	
Compressor	38.2		35.5	
He, L/A	48.25	1.1	48.25	1.1
Evaporator, A	70.1	1.58	70.1	1.58
Evaporator, L			5.0	0.06
Condenser	63.1	1.42	75.0	1.66
2. Condenser	51.9	1.09	51.9	1.09
Fans	43.4		47.7	
Heater	15		15	
Reg. He	10		13	
Refrigerant	28.3		34.6	
Valves	41.3		41.3	
Pump			<u>3</u>	
M _{ecs}	515.7 lb/unit (1547.1 lb total)		584.3 lb/unit	
M _{eh} , Engine Hp Wt	70.3		76.3	
M _{th} , Engine Th Wt	<u>25.2</u>		<u>25.2</u>	
M _{ecse}	611.2 lb/unit		683.8 lb/unit	
3 units	1833.6 lb		2051.4 lb	
1.25 M _e , Coolant	3999		4587	
M _{in} , Insulation	<u>1384.0</u>		<u>1384.0</u>	
M _{tw} , System	7216.6		8022.4	

TABLE 3
ENVIRONMENTAL CONTROL SYSTEM WEIGHT AND PENALTY

System	Bleed Air		Ram Air		Expendable Coolant		System Penalty		Total Dd Wt	Horsepower		Total Penalty/ Total Fuel P1
	\dot{W}_{tb}	W_{tb0}	$\frac{\dot{W}_{Tr3}}{\dot{W}_{Tr1}}$	\dot{W}_{Tr0}	$\frac{\dot{W}_{Te3}}{\dot{W}_{Te1}}$	\dot{W}_{Te0}	\dot{M}_{dw}	\dot{W}_{dw}	M_{tw}	hp	W_{hp}	$P1/P1_f$
	lb/min	lb	lb/min	lb	lb/min	lb	lb	lb	lb	hp	lb	lb
(1)A-1	500	8614.2	$\frac{1251}{900}$	4165.6			2201.7	3588.8	3585.7			$\frac{18,624.6}{14,166.9}$
(2)A-2	250	4365	$\frac{625}{625}$	2050.8			1139.1	1856.7	2523.1	26.1	78.9	$\frac{10,606.8}{7,211.7}$
(3)V-1	250	2820			$\frac{18.5}{16.8}$	4095.9	2652.6	4320	7216.6	378	1311.8	$\frac{12,537.6}{6,705}$
(4)V-2	250	2820			$\frac{23.5}{17.0}$	4698	2990.4	4875	8022.4	445	1530	$\frac{16,179}{7,284.6}$

(1) Bootstrap Air Cycle With Air Cooled Wall

(3) Vapor Cycle With Air Cooled Wall

(2) Semiclosed Bootstrap Air Cycle With Air Cooled Wall

(4) Vapor Cycle With Liquid Cooled Wall and Water Boiler

TABLE 3 (CONTINUED)

NOMENCLATURE

M_{dw}	=	$M_{ecse} + 0.25 M_e$, Includes all Fixed Weights except Insulation and expendable used
M_e	=	Total weight of Expendable used
M_{ecs}	=	Weight of ECS Components
M_{ecse}	=	$M_{ecs} + M_{eh} + M_{th}$, weight of ECS Components and engine weight Penalty
M_{eh}	=	Engine weight for horsepower, Equation 60
M_{in}	=	Thermal insulation weight
M_{te}	=	Total weight of Expendable coolant plus 25% reserve supply
	=	$1.25 M_e$
M_{th}	=	Engine weight for thrust drag, Equation 61
M_{tw}	=	Total fixed weight of the environmental control system, excluding fuel weight ($M_{ecsc} + 1.25 M_e + M_{in}$), lb
Pl_T	=	$Pl_{TOT} + W_{in}$
Pl_{TOT}	=	$W_{dw} + W_{Tb} + W_{Tr} + W_{hp} + W_{Te}$
W_{dw}	=	Fixed weight penalty of M_{dw}
W_{hp}	=	Horsepower weight penalty, Equation 20
W_{in}	=	Insulation weight
W_{Tb}	=	Bleed air penalty, Equation 19
\dot{W}_{tb}	=	Total bleed air flow
W_{Te}	=	Expendable weight penalty, Equation 12

\dot{W}_{Te_1} = Flow of expendable coolant at Mach 1 condition

\dot{W}_{Te_3} = Flow of expendable coolant at Mach 3 condition

W_{Tr} = Ram air penalty, Equation 10

\dot{W}_{Tr_1} = Total ram air flow at Mach 1 condition

\dot{W}_{Tr_3} = Total ram air flow at Mach 3 condition

W_{Ts} = Fixed weight penalty, Equation 3

total weight, M_{tw} , because this penalty determines part of the operation cost for the system.

Cycle V-2 had a total fuel penalty, Pl_f , that was only 8% greater than the preceding system. The total fixed weight and total weight penalty, Pl_T , was highest for all systems since the fixed weight of the components and water evaporated off in the boiler were high. This environmental control system was heavier than the preceding system since the evaporator cooling load was higher. The evaporator cooling load included the cooling load of the air/Freon evaporator, which was the same as the preceding system and cooling load of the liquid/Freon evaporator.

Even though the total weight penalty for Cycle V-3 was not considered, some interesting comparisons can be deducted. This system was similar to Cycle V-2 except the liquid condenser replaced the air water condenser (at $M = 3$ and $M = 1$) the thermal insulation was two inches instead of four inches and a recirculate air/bleed air heat exchanger was added. By using the weight penalty Pl_T and Pl_f of Cycle V-2, an approximated estimate of M_{tw} was 2872 lb and Pl_f was 5678 lb for Cycle V-3. However, this did not take into account the weight penalty for precooling the fuel, thermal insulation weight that may be needed to keep the fuel cool in the aircraft fuel tank, and added cost and logistic problems. Reference 19 considered a similar precooled fuel system and described the merits and disadvantages.

7. CONCLUSIONS

For this project, the selection of the most promising system(s) was based on the least total weight which is the sum of fixed weight, M_{tw} , and fuel penalty, Pl_f . The fuel weight penalty is that required to produce bleed air for the environmental control system and to overcome drag effects. In most situations the selection of the environmental control system is based on the total weight penalty and life cycle costs. These costs include cost of ownership and operation, cost of overhaul due to reliability effects of components and system, and costs associated

with normal servicing and maintenance. The weight penalty for all the environmental control systems were analyzed in detail except for the vapor Cycle V-3.

Based on the above selection criteria, the semiclosed bootstrap air cycle environmental control system and the semiclosed vapor Cycle V-1 were the most acceptable of systems analyzed. The semiclosed bootstrap air cycle environmental control system had the lowest fixed weight, M_{tw} . Both the vapor and semiclosed air cycle systems had the lowest fuel weight penalty, Pl_f . The pre-cooled fuel semiclosed vapor Cycle V-3 appears to be the best choice if the weight penalty associated with precooling the fuel heat sink were not considered.

Continued analysis of other system concepts appears desirable.

APPENDIX A

PERFORMANCE AND WEIGHT CALCULATIONS FOR THE SEMICLOSED BOOTSTRAP AIR CYCLE ENVIRONMENTAL CONTROL SYSTEM (Figure 6)

1. INTRODUCTION

The following calculations illustrate how an aircraft environmental control system performance and weight analysis was evaluated for the semiclosed bootstrap air cycle type of environmental control system. First, the performance of the environmental control system was evaluated, then the component analysis was conducted, and finally the weight penalties were determined for the air cycle.

2. CYCLE ANALYSIS

The performance of the cycle was determined by a reiteration method of calculating the values of pressure, temperature, and flow at each component. The procedures are as follows:

1. Certain values of pressure and temperature at various locations were dictated by specifications and they are defined as required values. These values were the air temperature, T_{to} , and pressure, P_{to} , at the turbine outlet and power balance factor between bootstrap compressor and turbine, Z_m .

2. The performance was determined after the inlet values of the bleed air, ram air, and transport liquid fluid were obtained. The input values were divided into the following two parts.

- a. A number of values (equal to the required values in number, and in this case, three) are defined as variables. These variables were adjusted to yield the required values. The variables were bleed air pressure, P_b , and liquid inlet temperature, T_{2i3} , T_{2i4} , and from values of T_{2i3} and T_{2i4} one obtains, the air temperature, T_{ci} , at the compressor inlet and the air temperature at the turbine inlet, T_{ti} , provided that the heat exchanger temperature effectiveness is known. Actually T_{ci} and T_{ti} are the values to be used in the iteration procedure.

b. The other input values were defined as specified input values and they were bleed air temperature, T_b , and flow, \dot{W}_b ; ram air temperature, T_r , pressure, P_r , and flow, \dot{W}_r ; and liquid flow, \dot{W}_{tf} .

Select some values for these three variables, P_b , T_{2i3} , T_{2i4} , to start with and after T_{ci} and T_{ti} are obtained it will yield a series of pressure, temperature and mass flow rate values at each component of the system. If those values differ substantially from the required values and specified input values, the trial and error procedure will be repeated by using a new set of values for those three variables. By repeated reiteration, a reasonable agreement between these two sets of values can be established.

Only the last iteration in the cycle analysis is presented below for the pressure, temperatures, and flows associated with the components of the environmental control system. The approach taken was to determine the total cooling load as in (Appendix B-5), the ram air conditions for the given flight profile, the bleed air pressure and the flow required at the inlet of Heat Exchanger Number 1 and then proceed to determine the performance of the environmental control system. Only Mach 3 flight condition evaluation is presented below.

a. Ram Air Conditions

The flight profile shown in Figure 11 was assumed for this analysis.

For the Mach 3 portion of the flight, the following ram air conditions were obtained:

The ambient temperature and pressure at 70,000 feet were obtained for ICOA standard day:

$$T_a = -67.4^\circ\text{F}$$

$$P_a = 0.65 \text{ psia}$$

The ram air temperature was obtained from Equation 25

$$T_r = 392.3 (1 + .2 (3)^2) = 1098.4^\circ R$$

The ram air total pressure was obtained from Equation 26

$$P_r = 0.65 (1 + .5 [(1 + .2(3)^2)^{3.5} - 1]) = 12.26 \text{ psia}$$

For the Mach 1 portion of the flight at 35,000 feet, the ambient temperature was $-65.6^\circ F$, ambient pressure was 3.47 psi, ram air temperature was $473^\circ R$, and ram air pressure was 5.01 psi.

For ground operation, the ambient temperature was assumed to be $80^\circ F$ and ambient pressure, 14.7 psia.

b. Bleed Air

The required bleed air pressure is a function of the cooling load and compartment temperature as determined in Appendix B-5. From this, the cooling load was 160,000 Btu/hr for the passenger and electronic equipment compartment and 259,500 Btu/hr for the heat load through the thermal insulation.

Since 50% of the compartment exhaust air is recirculated and mixed with the bootstrap turbine exhaust air, the turbine exhaust temperature, T_{to} , is determined from the equation

$$T_{ai} = ((T_{ao} + \Delta T_f) + T_{to})/2$$

and

$$T_{to} = 2 T_{ai} - T_{ao} - \Delta T_f$$

where T_{ai} is the cooling air temperature entering the compartment, T_{ao} is the air temperature of the air exhausted out of the compartment air passages, and ΔT_f is the increase in the temperature due to the compartment exhaust air being circulated through a fan and was obtained in the manner similar to Equation 28 as

$$\Delta T_f = T_{ao} (r_f^{(\gamma-1/\gamma)} - 1) / \eta_f$$

assuming a fan pressure ratio, r_f , of 1.07 for a two stage fan efficiency of 0.8, and knowing the other values from Appendix B, the exhaust temperature is

$$T_{to} = 2(507) - (565 + 565(1.07^{.286} - 1)/0.8) = 435.2^\circ R$$

By knowing the bootstrap turbine exhaust temperature, the compression ratio of the bootstrap compressor was determined from the energy balance between itself and the expansion turbine. Using Equation 45, the compression ratio was derived as

$$r_c = ([Z_m \eta_c (T_{ti} - T_{to})/T_{ci}] + 1)^{\gamma/(\gamma-1)} \quad (A-1)$$

The bootstrap turbine inlet temperature, T_{ti} , and compressor inlet temperature, T_{ci} , were accurately approximated through reiteration of the performance equations in this section as

$$T_{ti} = 620^\circ R, T_{ci} = 650^\circ R$$

since these temperatures were close to the heat sink liquid temperatures for Heat Exchanger Numbers 3 and 4, T_{2i3} and T_{2i4} , where

$$T_{2i3} = 640^\circ R, T_{2i4} = 610^\circ R$$

and a reasonable value for $Z_m \eta_c$ was 0.665 and η_t was 0.8. Then

$$r_c = \left((0.665 (620 - 435.2)/650) + 1 \right)^{3.5} = 1.83$$

The isentropic expansion temperature was derived from Equation 32 as

$$T'_{to} = 620 - (620 - 435.2)/0.8 = 389^\circ R$$

where the turbine adiabatic efficiency was assumed to be 0.8.

Assuming the air pressure out of the bootstrap turbine is 14.8 psia, the cooling turbine inlet air pressure was derived from Equation 31 as:

$$P_{ti} = 14.8 (620/389)^{3.5} = 75.7 \text{ psia}$$

Assuming a pressure drop of 1 psi through Heat Exchanger Number 4 (liquid/air), the outlet pressure at the bootstrap compressor was 75.7 psi. The pressure at the compressor inlet was

$$P_{ci} = 76.7/1.83 = 41.9 \text{ psia}$$

Assuming the pressure drop of 1 psi through either Heat Exchanger Number 3 (liquid/air) the Heat Exchanger Number 2 (air/air), and a 2 psi drop through Heat Exchanger Number 1 (air/air), the bleed air pressure was established at 46.9 psia.

Assuming an engine compressor efficiency of 0.8, the bleed air temperature was:

$$T_b = 1098 + 1098 (3.82^{0.26} - 1)/0.8 = 1670^\circ\text{R}$$

3. PERFORMANCE

For the Heat Exchanger Number 1 (air/air), the effectiveness was derived from Equation 52 as:

$$\eta_{hx1} = (T_{1i1} - T_{1o1}) / (T_{1i1} - T_r)$$

where T_{1i1} is the bleed air temperature into Heat Exchanger Number 1 in R, T_{1o1} is the bleed air temperature out of the Heat Exchanger Number 1 in R, T_r is the ram air temperature into Heat Exchanger Number 1 in R. Assuming an effectiveness of 0.85, the outlet heat exchanger bleed air temperature was:

$$T_{1o1} = 1670 - (1670 - 1098) 0.85 = 1184^\circ\text{R}$$

For Heat Exchanger Number 2 (air/air), assuming an effectiveness of 0.57 and an exhaust temperature out of the compartment wall at 565°R, the heat exchanger outlet bleed air temperature was:

$$T_{102} = 1184 - (1184 - 565) 0.57 = 831^{\circ}\text{R}$$

For Heat Exchanger Number 3 (liquid/air), assuming an effectiveness equal to 0.95, and liquid inlet temperature of 640°R, the outlet air temperature T_{103} (T_{Ci}) was:

$$T_{103} = 831 - (831 - 640) 0.95 = 649.5^{\circ}\text{R}$$

The isentropic bootstrap compressor exit temperature can be obtained from Equation 43 as:

$$T'_{co} = 650 (1.83)^{0.286} = 772.5^{\circ}\text{R}$$

And assuming a value for the bootstrap compressor efficiency, η_c , of 0.68, the actual compressor outlet temperature was determined from Equation 44 as

$$T_{co} = 649.5 + (772.5 - 649.5)/0.68 = 830.5^{\circ}\text{R}$$

For Heat Exchanger Number 4 (liquid/air), assuming an effectiveness of 0.95, a liquid inlet temperature of 610°R, the outlet air temperature T_{104} (T_{Ti}), was:

$$T_{104} = 830.5 - (830.5 - 610) 0.95 = 621^{\circ}\text{R}$$

The isentropic expansion temperature was determined from Equation 31 as:

$$T'_{To} = 621 (14.8/75.7)^{.286} = 389^{\circ}\text{R}$$

Assuming a turbine efficiency of 0.8, the actual turbine exhaust temperature was determined from Equation 32 as:

$$T_{To} = 621 - 0.8 (621 - 389) = 435.5^{\circ}\text{R}$$

The work of the bootstrap turbine Hp_t was

$$= (166.7) (0.24) (621 - 435.5)/42.4 = 175 \text{ hp}$$

The work of the bootstrap compressor Hp_c was

$$= 166.7 (0.24) (835.5 - 650)/42.4 = 175 \text{ hp}$$

The value of the power balance factor Z_m was assumed to be 0.975, however, using Equation 45, Z_m was

$$Z_m = 175/175 = 1$$

Therefore, the difference between the power balance factor, bootstrap turbine inlet, and outlet temperatures were small enough so that iteration was not repeated.

A summary of the performance of all flight profiles were:

		Mach 3	Mach 1	Ground
Ram Air Temp.	T_r , R	1098	473	540
Ram Air Pres.	P_r , psia	12.25	5.01	14.7
Bleed Air Temp.	T_b , R	1670	1029	850.5
Bleed Air Pres.	P_b , psia	46.9	40.8	44
Turbine Air Temp. (out)	T_{to} , R	438	460	486
Comp Pres Ratio	r_c	1.82	1.79	1.79
Turbo Pres Ratio	r_t	5.12	4.2	4.48

		Mach 3	Mach 1	Ground
Turbo Air Flow	\dot{W}_t , lb/min	83.35	66.15	81.3
Ram Air Flow	\dot{W}_r , lb/min	208.4	208.4	150

4. COMPONENT ANALYSIS

Basic design information required to determine weight and volume penalties were presented in the following analysis for the turbine/bootstrap compressor, axial fan, Heat Exchanger Number 1 (air/air), and engine.

a. Turbine Bootstrap Compressor

The turbine/bootstrap compressor was sized for Mach 3 condition and the weight and volume penalties were derived from the following procedure.

The turbine head was derived from Equation 30 as:

$$H_t = 778 (0.24) (621 - 435) = 34170 \text{ ft-lb}_f/\text{lb}_m$$

The turbine outlet flow, \dot{V}_t , in ft^3/sec , was

$$\dot{V}_t = \left(\frac{W}{60\rho}\right)_t = (83.35/60)/[(144 \times 15)/(53.3 \times 435)] = 15.0 \text{ ft}^3/\text{sec}$$

where ρ_t was the density of air at the turbine exhaust.

The optimum efficiency of a single-stage radial turbine occurs at a specific speed, N_s , of, or around, 60.0 and a specific diameter, D_s , of 1.7. For these conditions, the turbine speed was derived from Equation 29 as:

$$N_t = 60 (34170)^{.75} / (15.0)^{.5} = 38,900 \text{ rpm}$$

The diameter of the turbine was derived from Equation 33 as:

$$D_t = 12 (1.7)(15.0)^{.5} / (38900)^{.25} = 5.65 \text{ in}$$

The weight of the turbine/compressor unit was given in subsection III-5a as:

$$\begin{aligned} M_{tc} &= 100 (D_t/12)^3 \\ &= 100 (5.65/12)^3 = 10.3 \text{ lb} \end{aligned}$$

b. Recirculation and Exhaust Fan

The air circulated was sized for three axial fans in series with a pressure drop of 0.33 psi each and an optimum specific speed, N_s , of 1000. The weight and volume was derived in the following procedure.

The head of each fan was derived from Equation 46 as:

$$H_f = 144 (.33)/0.07 = 679 \text{ ft-lb}_f/\text{lb}_m$$

The required horsepower for each fan was derived in Equation 51 as:

$$\text{hp}_f = 679 (83.35)/(0.68 \times 33000) = 2.52 \text{ hp}$$

where η_f was estimated to be 0.68

The speed was derived from Equation 47 as:

$$N_f = 1000 (640)^{.75} / (83.35 / (60 \times 0.07))^{0.5} = 28560 \text{ rpm}$$

The diameter of the fan was derived from Equation 48 as:

$$D_f = 12.65 ((60 \times 19.8)/(\pi \times 28560))^{1/3} = 2.99 \text{ in}$$

The fan weight was estimated by Equation 49 as:

$$M_f = 60 (3.0/12)^3 + 0.5 = 1.4 \text{ lb}$$

The weight of the motor was estimated by Equation 50 as:

$$M_{mf} = 2.52 + 18 (3.0/12)^2 = 3.64 \text{ lb}$$

The total weight of all three fan systems

$$M_{tf} = 3 (1.4 + 3.6) = 15 \text{ lb}$$

c. Heat Exchanger Number 1, Air/Air

Heat Exchanger Number 1 (air/air) was designed using the analysis given in Appendix B-3. The heat exchanger core was of a single pass tubular type unit made of steel. In this analysis, the heat exchanger effectiveness, flow, and core pressure drop were estimated and the weight and volume of the heat exchanger were determined.

The design point selected for the heat exchanger was at Mach 3 condition since this segment of flight resulted in the highest heat load. Values selected for the design were η_{hxl} of 0.85, Z of 0.4 and Δp_{fb} and Δp_{fr} of 2 psi each. Using these values and Figure A-1, the number of heat transfer units, NTU, was found to be 2.7.

The density of the air was found by the formula

$$\text{Where } \rho_b \text{ air} = 2.7 P_{bave} / T_{bave} \quad (B-15)$$

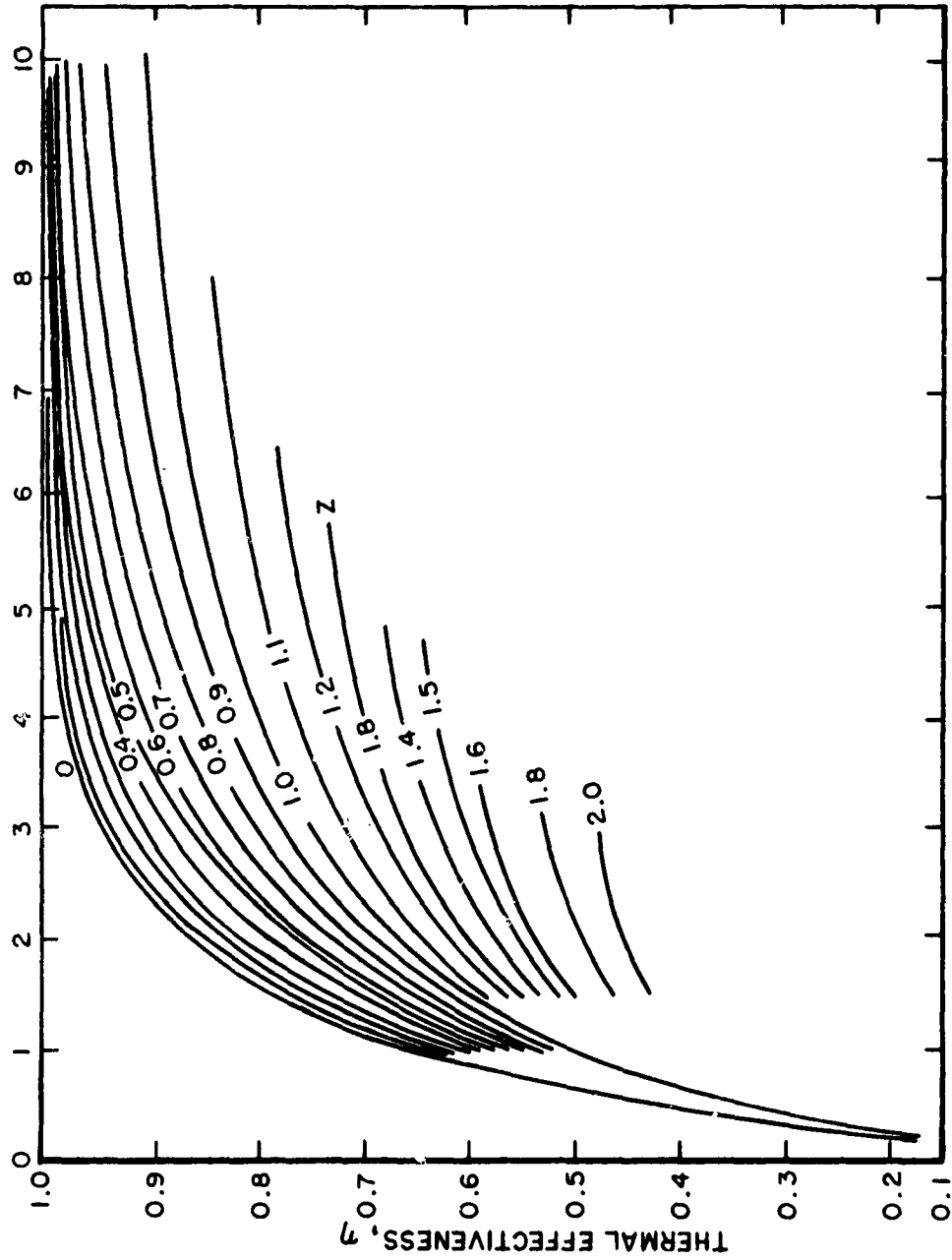
$$\begin{aligned} T_{bave} &= T_b - (T_b - T_r) \eta_{hxl} / 2 \quad (B-16) \\ &= 1670 - (1670 - 1098) 0.85 / 2 = 1427^\circ R \end{aligned}$$

and

$$\begin{aligned} T_{rave} &= T_r + (T_b - T_r) \eta_{hxl} (z) / 2 \quad (B-17) \\ &= 1098 + (1670 - 1098) 0.85 (.4) / 2 \\ &= 1195^\circ R \end{aligned}$$

then

$$\begin{aligned} \rho_b &= 2.7 (46 / 1427) = .0870 \text{ lb/ft}^3 \\ \rho_r &= 2.7 (11.35 / 1195) = 0.0256 \text{ lb/ft}^3 \end{aligned}$$



NUMBER OF HEAT TRANSFER UNITS, $NTU = UA/(Wc_p)$

Figure A-1 Thermal Effectiveness (η) for a One Pass Heat Exchanger

The free flow area, A_f , was determined from Equation B-13.
For the bleed side

$$A_{fb} = C'_b C''_b (\dot{W}_b \times UA_b / (P_b \times P_{fb} \times 144 \times 60))^{1/2}$$

where

$$C'_b = (2.82/64.4)^{1/2} = 0.2092$$

$$C'_r = (3.075/64.4)^{1/2} = 0.2185$$

and

$$C''_b = 2.34 \text{ and } C''_r = 3.64$$

From Equation B-19

$$UA_b = 83.35 \times 0.26 \times 2.7/60 = 0.98$$

Therefore

$$\begin{aligned} A_{fb} &= 0.2092 (2.34) [83.35 \times 0.98 / (0.0870 \times 2 \times 144 \times 60)]^{1/2} \\ &= 0.114 \text{ ft}^2 \end{aligned}$$

and

$$\begin{aligned} A_{fr} &= 0.2185 (3.46) [208.4 \times 0.98 / (0.0256 \times 2 \times 144 \times 60)]^{1/2} \\ &= 0.514 \text{ ft}^2 \end{aligned}$$

The frontal area, A_{face} , was derived from Equation B-20 as:

$$A_{face} = A_{fb} / k$$

where K_b was 0.125 and K_r was 0.33. Then

$$A_{\text{face } b} = 0.114/0.125 = 0.912 \text{ ft}^2$$

$$A_{\text{face } r} = 0.514/0.33 = 1.558 \text{ ft}^2$$

From Equation B-24, the core volume was:

$$V_{hx} = (0.912)^{1/2} (1.558) = 1.49 \text{ ft}^3$$

From Equation 53. the core weight was:

$$M_{hc} = 1.1 (19.2) 1.49 = 31.5 \text{ lb}$$

where C_i was 19.2 for a tubular core. From Equation 54, the heat exchanger weight was:

$$M_{hx} = 31.4 (12/1.51)^{.118} = 39.7 \text{ lb}$$

d. Engine Horsepower and Drag

The fixed weight penalty for extracting engine power involved horsepower and drag. Two coefficients were necessary to determine these weight penalties: specific engine weight/hp, SEWHP, and specific engine weight/thrust, SEWT. Typical value chosen for SEWHP was 0.26 lb/hp and for SEWT 0.2 lb/lb.

The engine fixed weight penalty for extracting engine compressor bleed air was determined for Mach 3 condition. The equivalent horsepower needed to compress the engine air at the bleed point was derived from Equation 17 as:

$$\begin{aligned} hp_{ec} &= \dot{W}_b c_p (T_b - T_r)/(42.4) \\ &= 83.35 \times .26 \times (1670 - 1098)/42.4 = 292.3 \text{ hp} \end{aligned}$$

The recirculation fan (Appendix A-4b) was operating at Mach 3 conditions and required three 2.4 hp motors. The other fans in the cycle were off.

The total fixed weight penalty for horsepower generation was derived from Equation 60 as:

$$M_{eh} = (292.3 + 3 (2.4)) 0.26 = 77.8 \text{ lb}$$

The engine fixed weight penalty for thrust loss charged to the environmental control system was sized for Mach 3 conditions. The thrust loss resulted from a drag when ram air was taken into the heat exchanger and engine. The relative velocity of the air was assumed to go from Mach 3 to almost zero velocity. An expansion nozzle was placed after the ram air went through the heat exchanger. Ram air through the nozzle was assumed to go from zero velocity to Mach 1 velocity, resulting in a partial thrust recovery.

The engine fixed weight penalty for thrust loss was derived from Equation 61 as:

$$M_{th} = \sum_{i=1}^n Th_r \text{ (SEWT)}$$

The total drag, ΣTh_r , for the bleed air and ram air was derived from Equation 7 as

$$\Sigma Th_r = [\dot{W}_b u_r + \dot{W}_r (u_r - u_{rho})] / (60 \text{ g}) \quad (A-2)$$

The ram air velocities, u_r in ft/sec, is

$$u_r = M(g\gamma R T_a)^{1/2} \quad (A-3)$$

$$= 3(49.1)(392.6)^{1/2} = 2912 \text{ ft/sec}$$

and the air velocity at the nozzle exit, u_{rho} in ft/sec, at Mach 1 is

$$u_{rho} = 49 M(T_{nhi})^{1/2} \quad (A-4)$$

where T_{nhi} is the temperature of the ram air at the outlet of Heat Exchanger Number 1. Then

$$u_{rho} = 49(1) (1312)^{1/2} = 1775 \text{ ft/sec}$$

The total drag is

$$\Sigma Th_r = [83.35(2912) + 208.4(2912-1775)]/60 \times 32.2 = 248 \text{ lb}$$

$$\text{and } M_{th} = 259(.2) = 49.6 \text{ lb}$$

e. Other Major Components

(1). Heat Exchanger Number 2, Air/Air

The component design of the Heat Exchanger Number 2 (air/air) was determined using the same technique as for the Heat Exchanger Number 1 (air/air). The heat exchanger has a single pass cross-flow arrangement plate/fin core weighing 27.3 lb and has a volume of 0.226 ft^3 . The heat exchanger was designed for an effectiveness of 0.566 and a ΔP of 2 psi for the high pressure side for Mach 3 flight condition.

(2). Liquid/Air Heat Exchanger

The component design of the liquid/air heat exchangers were determined using the technique outlined in Reference 15. The heat exchanger used a four pass flow arrangement and a tube/fine core with a liquid inside the tubes. The weight of each heat exchanger was 27.4 pounds and has a volume of 0.99 ft^3 . The effectiveness was 0.95 and the ΔP was 1 psi for the air side for Mach 3 flight conditions.

(3). Ram Air Fan

The fan was of axial type with three stages. The sizing of the fan was similar to that of the fan in Appendix A-4b.

The total weight of the ram air fan was

$$M_{tf} = 27.6 \text{ lb}$$

(4). Small Components

Weight of small components are summarized in the next section. Reference 20 summarizes typical weights of aircraft air conditioning components.

5. WEIGHT PENALTY

The weight penalty was based on the fixed weight penalty of the components of the environmental control system and (1) fuel expended in carrying fixed weight, (2) fuel used in operating engine compressor in obtaining pressurized bleed air, (3) fuel used in obtaining thrust power to overcome ram air drag, (4) fuel used to obtain horsepower for accessory requirements.

a. Fixed Weight

The total fixed weight of one environmental control unit, M_{ecs} , was:

	<u>1b</u>
Primary A/A Heat Exchanger Number 1	39.7
Regenerative A/A Heat Exchanger Number 2	27.3
Primary L/A Heat Exchanger Number 3	27.4
Turbine/Compressor	10.3
Secondary L/A Heat Exchanger Number 4	27.4
Axial Fans	57.6
Water Separator	11.0
<u>All Valves</u>	<u>51.5</u>
M_{ecs}	252.3 lb/unit

Including engine fixed weight penalty due to

Horsepower loss, M_{eh}	77.8
Thrust loss, M_{th}	<u>49.6</u>
$M_{ecse} (M_{dw})$	379.7 lb/unit
and for all three units	1139.1 lb

Including the insulation and for all three units

$$M_{tw} = M_{ecse} + M_{in} + 1.25 M_e$$

$$M_{tw} = 1139.1 + 1384.0 + 0 = 2523.1 \text{ lb}$$

b. Calculation of Total Penalty, Step Integration Method

(1). Fixed Weight Penalty Factor (W_{t_0}/W_s)

In order to determine the fixed weight penalty factor (W_{t_0}/W_s) from Equation 3, variables $(L/D)_i$, sfc_i , and x_i were required.

$$(L/D)_1 = 14 \text{ at Mach 1}$$

$$(L/D)_2 = 7.5 \text{ at Mach 3}$$

$$sfc_1 = 1.55 \text{ at Mach 1}$$

$$sfc_2 = 1.60 \text{ at Mach 3}$$

Let $x_i = sfc_i (t_i - t_{i-1}) / (L/D)_i$ where i was the flight condition,

Therefore

$$x_1 = 1.55 (0.75) / 14 = 0.083$$

$$x_2 = 1.60 (1.5) / 7.5 = 0.32$$

$$x_3 = 0.083$$

$$\sum_{i=1}^3 x_i = 0.486$$

Then $W_{ts_0}/W_s = \exp(0.486) = 1.626$

(2). Ram Air Penalty Factor $((\dot{W}'_{fr_i} / \dot{W}'_{r_i}) W'_i)$

From Equation 10, let the factor

$$W' = ((\exp(x_i) - 1) / a_i) \exp\left(\sum_{j=1}^{i+1} x_j\right)$$

Then

$$W'_1 = 45 (\exp(0.083) - 1)/0.083 = 47$$

$$W'_2 = (90 (\exp(0.32) - 1)/0.32) (\exp(0.083)) = 115$$

$$W'_3 = (45 (\exp(0.083) - 1)/0.083) (\exp(0.403)) = 70.1$$

And

$$\dot{W}'_{fr_1} / \dot{W}'_{r_1} = sfc_1 (u_r - u_{rho})_1 / (60 \times 32.2) \quad (9)$$

$$1.55 (974/60) / (60 \times 32.2) = 0.013$$

$$\dot{W}'_{fr_2} / \dot{W}'_{r_2} = 1.6 (3.0 \times 974 - 1778) / 60 / (60 \times 32.2) = 0.0157$$

$$\dot{W}'_{fr_3} / \dot{W}'_{r_3} = 0.013$$

Then the ram air penalty factors were

$$(\dot{W}'_{fr_1} / \dot{W}'_{r_1}) W'_1 = 0.013 (47) = 0.61$$

$$(\dot{W}'_{fr_2} / \dot{W}'_{r_2}) W'_2 = 0.0157 (115) = 1.805$$

$$(\dot{W}'_{fr_3} / \dot{W}'_{r_3}) W'_3 = 0.13 (70.1) = 0.91$$

(3). Bleed Air Penalty Factor $(W'_{Tb_i} / \dot{W}'_{b_i})$

From Equation 13 let the factor

$$(\dot{W}'_{fb_i} + \dot{W}'_{fdb_i}) W'_i = W'_{Tb_i}$$

where

$$\dot{W}'_{fb_i} / \dot{W}'_{b_i} = sfc'_i (hp_{ec_i}) / \dot{W}'_{b_i} \quad (15)$$

and

$$sfc'_i = sfc_i (550) / u_{r_i} \quad (A-7)$$

then

$$sfc'_1 = 1.55 (550)/974 = 0.876 \text{ lb/hp-hr}$$

$$sfc'_2 = 1.6 (550)/974 = 0.902 \text{ lb/hp-hr}$$

$$sfc'_3 = 0.876 \text{ lb/hp-hr}$$

and

$$\dot{W}_{fb_1} / \dot{W}_{b_1} = 0.876 (262) / (60 \times 83.35) = 0.046$$

$$\dot{W}_{fb_2} / \dot{W}_{b_2} = 0.902 (292.3) / (60 \times 83.35) = 0.0527$$

$$\dot{W}_{fb_3} / \dot{W}_{b_3} = 0.046$$

Then the bleed air penalty factors were

$$W'_{Tb_1} / \dot{W}_{b_1} = (0.046 + 0.013) 47 = 2.77$$

$$W'_{Tb_2} / \dot{W}_{b_2} = (0.0527 + 0.039) 115 = 10.55 \quad (A-8)$$

$$W'_{Tb_3} / \dot{W}_{b_3} = (0.059) 70.1 = 4.14$$

(4). Horsepower Extraction Penalty Factor (W'_{hp_i} / hp_i)

From Equation 24 let the factor

$$W'_{hp_i} = (sfc'_i hp_i) W'_i / 60$$

Then the horsepower extraction penalty factors were

$$W'_{hp_1} / hp_1 = 0.876 \times 47 / 60 = 0.686$$

$$W'_{hp_2} / hp_2 = 0.902 \times 115 / 60 = 1.73 \quad (A-9)$$

$$W'_{hp_3} / hp_3 = 0.876 \times 70.1 / 60 = 1.023$$

c. Penalty Determination

Penalty due to all fixed weight except insulation material and expendable coolant used, is designated as W_{dw} using Equation A-5, W_{Ts_0} was

$$W_{Ts_0} = W_s (W_{Ts_0}/W_s)$$

$$W_{Ts_0} = W_{dw} \text{ and } W_s = M_{dw}$$

$$W_{dw} = 379.7 (1.63) = 618.9 \text{ lb/unit}$$

$$= 1856.7 \text{ lb (3 units)}$$

Penalty Due to Insulation Weight (M_{in})

$$W_{Ts_0} = M_{in} (W_{Ts_0}/W_s)$$

$$W_{Ts_0} = W_{in} \text{ and } W_s = M_{in}$$

$$W_{in} = 1384 (1.63) = 2256 \text{ lb}$$

Using Equations 13 and A-8, the total penalty due to bleed air flow, W_{Tb} , was:

$$W_{Tb} = \dot{W}_{b_1} (W'_{Tb_1}/\dot{W}_{b_1}) + \dot{W}_{b_2} (W'_{Tb_2}/\dot{W}_{b_2}) + \dot{W}_{b_3} (W'_{Tb_3}/\dot{W}_{b_3})$$

$$= 83.35 (2.77) + 83.35 (10.55) + 83.35 (4.14)$$

$$= 1455 \text{ lb/unit}$$

$$= 4365 \text{ lb (3 units)}$$

Total Penalty Due to Ram Air Flow (W_{Tr})

Using Equations 10 and A-6, the total penalty due to ram air flow, W_{Tr} , was

$$W_{Tr} = \sum_{i=1}^3 \dot{W}'_i (W_{Tr_i}/W_{r_i})$$

$$\begin{aligned}
 &= 208.4 (0.61) + 208.4 (1.76) + 208.4 (0.91) \\
 &= 683.6 \text{ lb/unit} \\
 &= 2050.8 \text{ lb (3 units)}
 \end{aligned}$$

Penalty Due to Horsepower Extraction (W_{hp})

Horsepower extraction in flight involved the recirculation fan.

$$hp_1 = hp_2 = hp_3 = (2.52) 3 = 7.6hp$$

Using Equations 24 and A-9, the penalty due to the horsepower extraction, W_{hp} , was:

$$\begin{aligned}
 W_{hp} &= 7.6 (.686 + 1.73 + 1.023) = 26.1 \text{ lb/unit} \\
 &= 78.3 \text{ lb (3 units)}
 \end{aligned}$$

Total Penalty (Pl_{TOT})

$$\begin{aligned}
 Pl_{TOT} &= W_{dw} + W_{Tb} + W_{Tr} + W_{hp} \\
 &= 618.9 + 1455 + 683.6 + 26.1 \\
 &= 2783.6 \text{ lb/unit} = 8350.8 \text{ lb (3 units)}
 \end{aligned}$$

Total Penalty, Including the Thermal Insulation (all three units)

$$\begin{aligned}
 Pl_T &= Pl_{TOT} + W_{in} \\
 &8350.8 + 2256 = 10606.8 \text{ lb (3 units)}
 \end{aligned}$$

Total Fuel Penalty Except for Thermal Insulation

$$\begin{aligned}
 Pl_f &= Pl_{TOT} - M_{ecse} - 1.25M \\
 &8350.8 - 1139.1 - 0 = 7211.7 \text{ lb (3 units)}
 \end{aligned}$$

Total Fuel Penalty

$$\begin{aligned}Pl_{Ts} &= Pl_T - M_{ecse} - M_{in} - 1.25M \\&= 10606.8 - 1139.1 - 1384 - 0 \\&= 8082.7 \text{ lb (3 units)}\end{aligned}$$

APPENDIX B

WEIGHT AND PERFORMANCE ANALYSIS

1. FIXED WEIGHT PENALTY (W_{TS})

The fixed weight penalty, W_{TS} , is composed of the fixed weight of the environmental control system components and the amount of fuel expended by the plane in carrying the fixed weight, W_{fs} , for a time interval k . The step change representing the rate of decrease in weight is

$$W_{TS_{k+1}} - W_{TS_k} = -(t_{k+1} - t_k)[W_{TS} (\text{sfc}/(\text{LD}))]_{t_k} \quad (1)$$

Equation 1 can also be expressed in the differential form as:

$$dW_{TS}/dt + a W_{TS} = 0 \quad (2)$$

The solution of Equation 2 for any section of the flight profile is

$$W_{TS} = A' \exp(-at) \quad (B-1)$$

where A' is a constant of integration. When t_i is defined as the beginning of the time interval i , the following equation can be written in terms of t_i :

$$W_{TS} = W_{TS_i} \text{ at } t = t_i$$

$$\text{so } W_{TS_i} = A' (\exp(-at_i))$$

$$\text{where } A = W_{TS_i} (\exp(at_i))$$

and at the end of the time interval i ,

$$W_{TS} = W_{TS_{i+1}} \text{ at } t = t_i + 1$$

and

$$W_{TS_i}/W_{TS_{i+1}} = \exp(a_i(t_{i+1} - t_i)) \quad (B-2)$$

During the first segment of the flight (assumed to be at Mach 1 speed), the following definitions are given:

$$W_{Ts_i} = W_{Ts_0}, W_{Ts_{i+1}} = Y_{s_1} \text{ and } a = a_1$$

where W_{Ts_0} is the sum of the fixed weight of the environmental control system, W_s , and weight of the fuel expended for the total flight, W_{fs} and where Y_{s_1} is the fixed weight of the fuel expended for the total flight less the first segment of the flight. The weight penalty for the first segment is:

$$W_{Ts_0}/Y_{s_1} = \exp(a_1(t_1 - t_0)) \quad (B-3)$$

Similarly, the second segment of the flight (assumed to be at Mach 3 speed), can be described as follows:

$$Y_{s_1}/Y_{s_2} = \exp(a_2(t_2 - t_1)) \quad (B-4)$$

$$a = a_2$$

where Y_{s_2} is the fixed weight of the environmental control system and weight of the fuel expended for the total flight less the first two segments of flight. Substituting equation (B-4) into Equation (B-3)

$$W_{Ts_0} = Y_{s_2} \exp(a_1 t_1 + a_2(t_2 - t_1)) \quad (B-5)$$

If "n" is used to designate the last segment of the flight, it will yield the following relation.

$$Y_{s_{n-1}}/Y_{s_n} = \exp[a_n(t_n - t_{n-1})] \text{ and } a = a_n$$

and

$$Y_{s_n} = W_s$$

where $Y_{s_{n-1}}$ is the fixed weight of the environmental control system and weight of the fuel expended for the total flight less the first n-1 segments.

By using the preceding equation and substituting for the Y equations, finally, W_{Ts_0} can be defined as

$$W_{Ts_0} = W_s \exp \left(\sum_{i=1}^n a_i (t_i - t_{i-1}) \right) \quad (3)$$

2. RAM AIR PENALTY (W_{Tr})

The ram air penalty is defined as the fuel penalty that is expended in the engine so that the additional thrust produced will offset the drag loss, W'_{fr} in lb, plus the extra fuel, W_{fr} in lb, expended in carrying the fuel W'_{fr} up to the point where it is expended in the engine. For a finite time change, the difference in ram air penalty is

$$W_{Tr_{k+1}} - W_{Tr_k} = -(t_{k+1} - t_k) \left[W_{Tr} (sfc/(L/D)) \right] t_k + W'_{fr} (t_{k+1} - t_k) \quad (4)$$

where k is an interval index and W'_{fr} is a constant fuel flow rate expended in the engine to overcome the ram air drag in lb/min.

Equation 4 can be expressed in the differential form as

$$dW_{Tr}/dt + a W_{Tr} + W'_{fr} = 0 \quad (5)$$

The solution of Equation 5 for any section of the flight profile is:

$$W_{Tr} = A' \exp (-at) - b/a \quad (B-6)$$

where A' is the constant of integration and b is W'_{fr} . When t_i is the beginning of the time interval i , the following expressions can be written in terms t_i where $W_{Tr} = W_{Tr_i}$ at $t = t_i$

$$W_{Tr_i} = A' \exp (-a t_i) - b/a$$

where

$$A' = (W_{Tr_i} + b/a) \exp (a t_i)$$

Substituting A' into Equation B-6

$$W_{Tr} = (W_{Tr_i} + b/a) \exp (a (t_i - t)) - b/a$$

and at the end of the time interval i , $W_{Tr} = W_{Tr_{i+1}}$ for $t = t_{i+1}$

Then

$$(W_{Tr_i} + b/a)/(W_{Tr_{i+1}} + b/a) = \exp (a (t_{i+1} - t_i))$$

During the first segment of the flight (assumed to be at Mach 1), the following definitions are given:

$$W_{Tr_i} = W_{Tr_0}, W_{Tr_{i+1}} = Y_{r_1}, a = a_1, \text{ and } b = \dot{W}'_{fr_1}$$

where Y_{r_1} is the weight of the fuel expended in the total flight less the first segment of the flight, \dot{W}'_{fr_1} is a constant fuel rate for the first segment of flight due to the ram air penalty in lb/hr, and W_{Tr_0} is the weight of the fuel expended for the total flight due to ram air penalty.

Then

$$(W_{Tr_0} + \dot{W}'_{fr_1}/a_1)/(Y_{r_1} + \dot{W}'_{fr_1}/a_1) = \exp (a_1 t_1) \quad (B-7)$$

Similarly, the second segment of the flight (assumed to be at Mach 3), can be described as follows:

$$(Y_{r_1} + \dot{W}'_{fr_2}/a_2)/(Y_{r_2} + \dot{W}'_{fr_2}/a_2) = \exp (a_2 (t_2 - t_1)) \quad (B-8)$$

where Y_{r_2} is the weight of the fuel expended in the total flight less the first two segments of the flight, \dot{W}'_{fr_2} is a constant fuel rate for the second segment of the flight due to the ram air penalty in lb/hr, and a is equal to a_2 .

Substituting Equation B-8 into Equation B-7 and solving for Y_{r_2}

$$Y_{r_2} = \left[\frac{W_{Tr_0}}{e^{x_1}} + \frac{\dot{W}'_{fr_1}}{a_1 e^{x_1}} - \frac{\dot{W}'_{fr_1}}{a_1} + \frac{\dot{W}'_{fr_2}}{a_3} - e^{x_2} \frac{\dot{W}'_{fr_2}}{a_2} \right] / e^{x_2} \quad (B-9)$$

where $x_i = a_i (t_i - t_{i-1})$.

Similarly, the third segment of the flight (assumed to be at Mach 1), can be described as follows:

$$(Y_{r_2} + \dot{W}'_{fr_3}/a_3) / (Y_{r_3} + \dot{W}'_{fr_3}/a_3) = \exp(a_3(t_3 - t_2)) \quad (B-10)$$

where Y_{r_3} is the weight of the fuel expended in the total flight less the first three segments of the flight, \dot{W}'_{fr_3} is a constant fuel rate for the third segment of the flight due to the ram air penalty in lb/hr, and a is equal to a_3 .

If $Y_{r_3} = 0$ where $n = 3$ and substituting Y_{r_2} into Equation B-10, it leads to

$$W_{Tr_0} = \frac{\dot{W}'_{fr_1}}{a_1} (e^{x_1} - 1) + \frac{\dot{W}'_{fr_2}}{a_2} (e^{x_2} - 1) e^{x_1} + \frac{\dot{W}'_{fr_3}}{a_3} (e^{x_3} - 1) (e^{x_1} e^{x_2}) \quad (B-11)$$

If the weight penalty is expanded for n terms, W_{Tr_0} can be given by

$$W_{Tr_0} = \sum_{i=1}^n \left[\dot{W}'_{fr_i} \left(\frac{e^{x_{i-1}}}{a_i} \right) \exp \left(\sum_{j=i}^{i-1} x_j \right) \right] \quad (6)$$

where $x_j = a_j(t_j - t_{j-1})$.

3. AIR/AIR HEAT EXCHANGER (Reference 14)

In this subsection, an approximate method is considered for the determination of the cross-flow heat exchanger. These approximations are made in an effort to reduce the complexity of design procedures.

The air/air heat exchanger used for aircraft applications is of a plate/fin or tube/fin type construction. Only the one-pass heat exchanger type, as shown in Figure 14, will be considered for this report. The material for the heat exchanger is aluminum for temperatures below 600°F and stainless steel for temperatures above 600°F.

The following formulas are the conclusions drawn from the heat exchanger calculations.

The free flow area, A_f in ft^2 derived from basic heat transfer equations, is (Reference 14)

$$A_{f_1} = \left[\left(\frac{\alpha_1}{2g} \right) \left(\frac{f_1}{j_1} \right) \frac{1}{\eta_{o_1}} \left(1 + \frac{(\eta_o hA)_1}{(\eta_o hA)_2} \right) \frac{\dot{W}_1 (UA)_1}{60\rho_1 \Delta P_1} \right]^{1/2} \quad (\text{B-12})$$

where A is the total heat transfer area in ft^2 , h is the heat transfer coefficient in $\text{Btu/sec ft}^2 \text{ } ^\circ\text{F}$, U is the overall heat transfer coefficient in $\text{Btu/sec ft}^2 \text{ } ^\circ\text{F}$, ρ is the density of air in lb/ft^3 , ΔP is the pressure drop in lb/in^2 , α is $P_r^{2/3}/c_p$ in $\text{lb } ^\circ\text{F/Btu}$, P_r is the Prandtl number (dimensionless), c_p is the specific heat at constant pressure in $\text{Btu/lb } ^\circ\text{F}$, f is the friction factor, defined on the basis of surface shear stress (dimensionless), j is the Colburn modulus (dimensionless), η_o is the total surface temperature effectiveness, W is the air flow in lb/min , subscripts (1) and (2) are for side 1 and 2 of the heat exchanger, respectively.

$$A_{f_1} = \frac{C' C''}{144 \times 60} \left[\frac{W U A}{\rho \Delta P} \right]_1 \quad (\text{B-13})$$

where

$$C' = (\alpha/2g)^{1/2}$$

$$C'' = \left[\left(\frac{f}{j} \right)^{1/2} \frac{1}{n_{o1}} \left(1 + \frac{(n_o h A)_1}{(n_o h A)_2} \right) \right]^{1/2} \quad (B-14)$$

A reasonable value used in estimating C'' is 3.06 for plate/fin cores, 2.34 for inside tubes, 3.46 for outside of tubes, and ΔP_1 and ΔP_2 is in the order of 2 psi.

The average density of the air, in lb/ft^3 , on either side of the heat exchanger is found by standard gas law formula

$$\rho_1 = P_{1ave}/R T_{1ave}$$

$$\rho_2 = P_{2ave}/R T_{2ave} \quad (B-15)$$

where

$$P_{1ave} = P_{1i} - 0.5 \Delta P_1$$

and P_{1i} is the pressure of the fluid into the heat exchanger in psi, ΔP_1 is $(P_{1i} - P_{1o})$ in psi, and P_{1o} is the pressure of the fluid out of the heat exchanger in psi. The term P_{2ave} is derived in a similar manner as P_{1ave} . The term T_{1ave} is

$$T_{1ave} = T_{1i} - \left(\frac{T_{1i} - T_{2i}}{2} \right) \eta_{1hx} \quad (B-16)$$

and T_{1i} is the temperature of the fluid into heat exchanger on side 1 (hot fluid being cooled) in $^{\circ}\text{R}$, T_{2i} is the temperature of the fluid into heat exchanger on side 2 in $^{\circ}\text{R}$, and temperature effectiveness, η_{1hx} and η_{2hx} are defined as $(T_{1i} - T_{1o})/(T_{1i} - T_{2i})$ and η_{2hx} is $(T_{2o} - T_{2i})/(T_{1i} - T_{2i})$ respectively. Similarly,

$$T_{2ave} = T_{2i} + \frac{(T_{1i} - T_{2i})}{2} \eta_{2hx} \quad (B-17)$$

The terms η_{hx2} and η_{hx1} are related by

$$\eta_{2hx} = A\eta_{1hx} \quad (B-18)$$

and

$$Z = (\dot{W} c_p)_1 / (\dot{W} c_p)_2$$

when $(\dot{W} c_p)_1 < (\dot{W} c_p)_2$

Since a heat exchanger has only one UA value,

$$(UA)_1 = (UA)_2$$

where

$$UA = (NTU) \dot{W} c_p \quad (B-19)$$

and NTU is the number of heat transfer units which can be obtained from Figure A-1.

The frontal area, A_{face} , is

$$A_{face} = A_f / K \quad (B-20)$$

Typical values of K in design of heat exchangers are 0.18 for the high pressure side and 0.6 for the low pressure side, when using a plate/fin core. Also, typical values of K for a tube/fin core is 0.125 for the high pressure side and 0.33 for the low pressure side.

Assuming that the largest face area is a square and the maximum core volume V_{hx} in ft^3 , is a cube

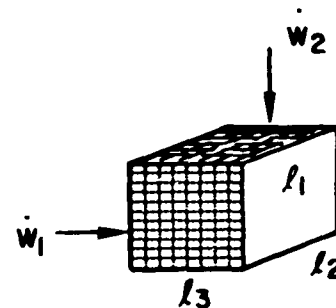
$$V_{hx} = \ell_1 \ell_2 \ell_3 \quad (B-21)$$

$$\ell_1 = \ell_3$$

$$A_{f_1} = l_1 l_3 = l_1^2 \quad (B-22)$$

$$A_{f_2} = l_1 l_2 \quad (B-23)$$

$$V_{hx} = (A_{f_1})^{1/2} A_{f_2} \quad (B-24)$$



4. WATER BOILER

A water boiler is used to extend the capability of the available ram air and fuel heat sink. Use of water as an expendable liquid is common for a high speed aircraft (e.g. USAF XB-70). For this project, the water boiler operates with a water/Freon section of the condenser and water pump as shown in Figure 25.

The total internal volume of a water boiler, V_b in ft^3 is

$$V_b = M_w / P_w \quad (B-25)$$

where the mass of the water is

$$M_w = (Q_1 / h_1) t \quad (B-26)$$

and P_w is the density of water in lb/ft^3 , Q_1 is the heat load in Btu/hr , h_1 is the latent heat of water under operating conditions in Btu/lb .

The water boiler storage tank weight, M_{st} consist of the mass of water, M_w , stored and the integral container, M_c . The container is assumed cubic in shape and made of aluminum. The container wall thickness is held constant at 0.050 inches with 100% of the container metal weight allowed for stiffeners and supporting structure is (Reference 19)

$$M_c = (12) V_b^{2/3} t_{al} \rho_{al} \quad (B-27)$$

where t_{al} is the thickness of the container in ft and ρ_{al} is the density of the aluminum in lb/ft³. The total system weight, M_{st} in lb, is

$$M_{st} = M_c + M_w \quad (B-28)$$

5. COMPARTMENT PERFORMANCE CALCULATIONS FOR THE SEMICLOSED BOOT-STRAP AIR CYCLE ENVIRONMENTAL CONTROL SYSTEM

The heat loads are generated by two sources, the external and the internal sources. The external heat load is the aerodynamically induced heat load, Q_2 , and the internal heat loads are due to passenger and electronic equipment heat sources.

The aerodynamically induced heat load, in Btu/hr, through the compartment wall thermal insulation of thickness X_{in} is

$$Q_{in} = k_{in} A_c (T_{fg} - T_{cw}) / X_{in} \quad (56)$$

where T_{fg} is the fuselage temperature in R and T_{cw} is the compartment wall temperature in R. The surface area of the compartment wall is

$$A_c = P_c \ell_c$$

where P_c is the perimeter of the compartment wall in ft and ℓ_c is the length of the wall. For this project, P_c is 34.6 ft, ℓ_c is 200 ft, k_{in} is 0.38 Btu/hr °F ft, X_{in} is 0.33 ft, T_f is assumed to be 942°R (Reference 17), and the average wall temperature, T_{cw} , is 547°R.

Then

$$Q_{in} = 0.0317 (34.6 \times 200) (942 - 547) / 0.333 = 259,500 \text{ Btu/hr}$$

The internal heat load, Q_c , due to the electronic equipment heat source is estimated to be around 36,000 Btu/hr. The passenger heat load, Q_p , is 122,000 Btu/hr, based on 256 passengers generating 475 Btu/hr per person.

Compartment Temperatures

The cooling air temperature, T_{ai} , required into the compartment is derived as

$$T_{ai} = T_{ct} - Q_p / (\dot{m}_c c_p)$$

where \dot{m}_c is the air flow into the compartment in lb/hr and T_{ct} is the average temperature in the compartment. This air flow, \dot{m}_c , based on 20 ft³/min per passenger is:

$$\dot{W}_c = (20 \text{ ft}^3/\text{min} \times 256 \text{ people}) / 13.3 \text{ ft}^3/\text{lb} = 385 \text{ lb/min}$$

The compartment temperature was set at 69°F for this example. Then

$$T_{ai} = 69 - 122,000 / (.24 \times 385 \times 60) = 47^\circ\text{F}$$

The required air flow to cool the electronic equipment, assuming a ΔT of 22°F and an inlet temperature of 47°F, is

$$\dot{W}_{el} = 36,000 / (.24 \times 22 \times 60) = 115 \text{ lb/min}$$

The total compartment air flow, W_{tc} is 500 lb/min. This air flow is obtained from three semiclosed bootstrap air cycle environmental control systems, supplying 167.3 lb/min per system. Two environmental control systems supply air to the passenger compartment and the third system splits the cooling air between the passenger compartment and pilot compartment where most instruments are located as shown in Figure 4.

By assuming all the aerodynamically induced heat load is absorbed by the coolant, the temperature of the air exhausting out of the passenger compartment air passages wall is

$$T_{aw_o} = T_{ct} + Q_{in} / (c_p \dot{m}_{tc}) = 69 + 259,500 / (0.24 \times 500 \times 60) = 105^\circ\text{F}$$

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